Inter laboratory comparison on Industrial Computed Tomography

CIA-CT comparison. Final Report

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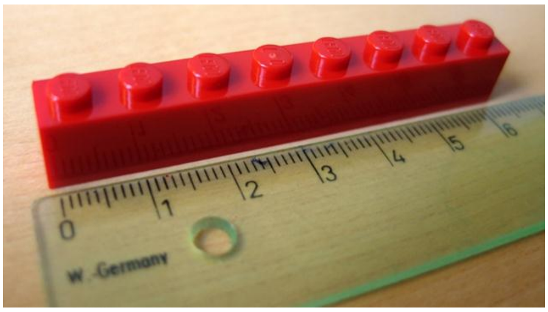

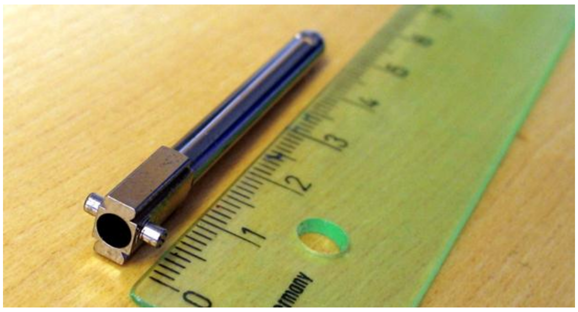

Final report

September 2013

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Abstract

An interlaboratory comparison on industrial X-ray Computed Tomography (CT) was organized by the Centre for Geometrical Metrology (CGM), Department of Mechanical Engineering, Technical University of Denmark (DTU) and carried out within the project “Centre for Industrial Application of CT scanning - CIA-CT”. In the comparison, 27 laboratories from 8 countries were involved, and CT scanned two items selected among common industrial parts: a polymer part and a metal part. Altogether, 27 sets of items were circulated in parallel to the participants. Different measurands are considered, encompassing diameters, roundness, and lengths. The results of each participant are kept confidential. Each participant can identify their own results in this report using an anonymous identification number provided by the coordinator. Measuring instructions distributed by the coordinator were followed by all participants without problems. Participants carried out measurements and sent their results to the coordinator. All single items were measured by the coordinator using coordinate measuring machines before and after circulation. Both the metal item and the plastic item have shown a good stability over the total period of approx. 6 months. Depending on item and measurand, reference expanded uncertainties (k=2) ranging from approx. 1.5 µm up to approx. 5.5 µm were estimated. The expanded uncertainties stated by the participants are in the range 8-12 µm for both items and all measurands. Results by the single participants were compared with the reference values provided by the coordinator through the E_n value, where $|E_n| < 1$ indicates agreement between measurement results while $|E_n| \geq 1$ shows disagreement. Out of a total of 167 single results obtained by the participants using CT scanning, 55% of the measurements yield $|E_n|$ values less than 1, and 45% larger than 1. Systematic errors were detected for some participants on the diameters and lengths, for both plastic and metal items. The roundness measured by the participants for both plastic and metal items was higher than the unfiltered reference value. A clear influence from the surrounding wall thickness on the measurement of roundness was documented for the metal item. The comparison shows that CT scanning on small industrial parts, generally speaking, is connected with uncertainties in the range 8-53 µm, as compared to an uncertainty range of 1.5-5.5 µm using CMMs. Each participant can use the comparison results in the report to investigate the presence of systematic errors or an underestimation of uncertainties. Statistics related to the used equipment and procedures show that participants, in general, have followed state of the art procedures for their measurements. The industrial items are suitable artefacts for CT measurements of this kind, and each participant has been offered to keep a set used for the measurements in the comparison.

Preface

The ‘CIA-CT comparison - Inter laboratory comparison on industrial Computed Tomography” was organized by DTU Department of Mechanical Engineering within the Danish project “Centre for Industrial Application of CT scanning - CIA-CT”, co-financed by the Danish Ministry of Science, Technology and Innovation. The project team at DTU Department of Mechanical Engineering, Centre for Geometrical Metrology (CGM) was composed by:

Leonardo De Chiffre, Professor
Jais Angel, Ph.D. Student
René Sobiecki, Engineer Assistant
Jakob Rasmussen, Metrology Technician
Erik Larsen, Quality and Metrology Engineer, IPU Technology Development

The participants involved in the comparison were:

3D-CT A/S	(Denmark)
BAM Federal institute for materials research and testing	(Germany)
Braun GmbH, Precision Measurement , CAQ-Engineering	(Germany)
Carl Zeiss IMT GmbH	(Germany)
Danish Technological Institute (DTI)	(Denmark)
Fraunhofer Development Center for X-ray Technology (EZRT)	(Germany)
GE Measurement & Control (Zebicon A/S)	(Denmark)
GRUNDFOS A/S	(Denmark)
Hexagon Metrology Inc	(USA)
Huddersfield University (HUD)	(UK)
Institute of Manufacturing Metrology, Friedrich-Alexander-University Erlangen-Nuremberg (FMT)	(Germany)
Katholieke Universiteit Leuven	(Belgium)
LEGO System A/S	(Denmark)
National Metrology Institute of Japan, National Inst. of Advanced Ind. Science and Technology (AIST)	(Japan)
National Physical Laboratory (NPL)	(UK)
Nikon Metrology UK	(UK)
Novo Nordisk A/S, Device R&D	(Denmark)
Novo Nordisk A/S, DMS Metrology & Calibration	(Denmark)
SGS Institut Fregenius GmbH	(Germany)
SIMTech	(Singapore)
UNCC, Center for Precision Metrology	(USA)
University of Padova (UNIPD)	(Italy)
University of Southampton	(UK)
Wenzel Volumetrik GmbH	(Germany)
Werth Messtechnik GmbH	(Germany)
Mikroproduktionstechnik, Fraunhofer-Institut für Produktionsanlagen und Konstruktionstechnik (IPK)	(Germany)
YXLON International GmbH	(Germany)

Reference measurements at CGM were performed by René Sobiecki, Jakob Rasmussen and Erik Larsen.

The valuable support of Dr. Alan Wilson, NPL in connection with some supplementary CMM measurements is gratefully acknowledged.

Valuable contributions were given by the following persons at two preparatory workshops held at DTU in September and November 2012, and at a final workshop in June 2013.

Andreas Staude, BAM
Angela Cantatore, Metrologic ApS
Armin Löwenstein, Fraunhofer IPK
Brian Hougaard Sørensen, LEGO System A/S
Britta Schlüter, SGS Institut Fregenius GmbH
Charlotte Haagensen, Novo Nordisk A/S
Ecaterina Schuster, Carl Zeiss IMT GmbH
Isabel Erbeck, YXLON International GmbH
Jan Lasson Andreasen, Novo Nordisk A/S
Jan Møgelmose, KYOCERA UNIMERCO Tooling A/S
Jens Bo Toftegaard, DTI
Joachim Maaß, Braun GmbH
Jochen Hiller, Carl Zeiss IMT GmbH
Kim Demant Andersen, Zebicon A/S
Kim Skov Mortensen, 3D-CT A/S
Lars Brøndbjerg, 3D-CT A/S
Lars Pejryd, Örebro University
Lorenzo Carli, Novo Nordisk A/S
Maria Holmberg, DTI
Mark Mavrogordato, University of Southampton
Markus Bartscher, Physikalisch-Technische Bundesanstalt (PTB)
Martin Simon, Wenzel Volumetrik GmbH
Niels Thestrup Jensen, DTI
Paul Bills, University of Huddersfield
Pavel Müller, LEGO System A/S
Peder Bay, Carl Zeiss IMT GmbH
Peder Pedersen, DTI
Per René Schmidt, LEGO System A/S
Simone Carmignato, UNIPD
Till Nuernberger, Werth Messtechnik GmbH
Trine Sørensen, Novo Nordisk A/S
Wenjuan Sun, NPL
Willy Callin, Braun GmbH
Ye Tan, KU Leuven
Yongying Dai, Novo Nordisk A/S

The kind help from Dr. Simone Carmignato, University of Padova, in connection with the final review of this report is gratefully acknowledged.

Thanks to all, especially to the participants, for their contributions to the project.

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1. Project

The project was organized and coordinated by CGM, taking advantage of previous experience in other inter laboratory comparisons [Hansen et al., 1996] [De Chiffre et al., 2004] [Angel et al., 2012].

Two items were used, selected among representative industrial parts: a polymer part (Item 1) and a metal part (Item 2). The items were measured by 27 participants from Belgium, Denmark, Germany, Italy, Japan, Singapore, UK and USA. The comparison was based on a set of two items for each participant. All sets were circulated in parallel, one to each participant, with the main circulation completed in 1 month, and 15 months from project start to final report. The main circulation took place in week 2 to 4 (7th January to 27th January) 2013, and was completed in July 2013. Some participants joined the project later in the process during spring 2013.

The items were measured according to a protocol provided by the coordinator containing documentation, logistics, and measuring and reporting instructions [Technical Protocol]. The protocol also included reporting forms to fill out. The results of each participant are kept confidential. Each participant can identify their own results in this report using an anonymous identification number provided by the coordinator.

After completion of the comparison, each participant has been offered to keep a set used for the measurements.

1.1. Project aims

The comparison has aimed to collect information about measurement performance in state-of the-art industrial X-ray Computed Tomography (CT). Since CT has entered the field of manufacturing and coordinate metrology, evaluation of uncertainty of measurement with assessment of all influence contributors has become a most important challenge related to the establishment of traceability. This investigation focuses mainly on operator influences on the measurement result. The main goals of the project can be summarized as follows:

- To test applicability of CT for measurement on small objects, commonly measured in industry, which are more representative than reference artefacts.
- To evaluate the impact of instrument settings and operator decisions on the measurement of items of two different materials and geometries.
- To investigate measurement errors and their causes.
- To collect and share knowledge on practical aspects related to the traceability of measurements using industrial CT.

1.2. Project management and time schedule

The involved project phases were:

1. Plan, participants' definition.
2. Item calibrations.
3. Circulation.
4. Analysis of results.
5. Reporting and dissemination.

The timeline in Figure 1 gives an indication of the different phases.

A final workshop was held at DTU the 20th June 2013, where the participants have discussed and given contributions to the analysis of the comparison. Due to a delay of three participants' results due to technical issues, and because of a cooling compressor breakdown at CGM during the re-measurements after circulation, a new series of reference measurements was introduced in August 2013, along with supplementary measurements of some items at NPL.

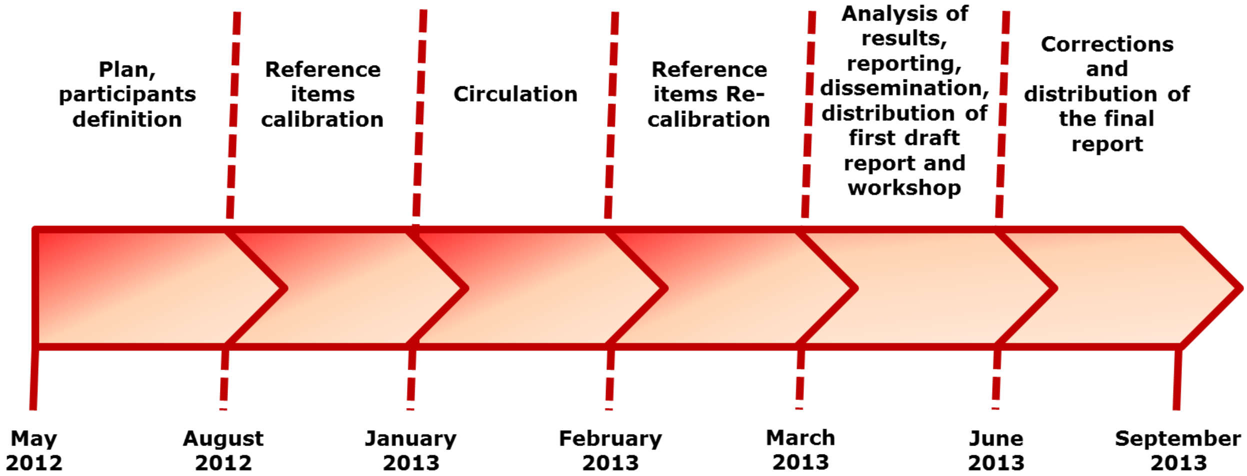


Figure 1: Time schedule for the CIA-CT comparison.

1.3. Participants

A total number of 27 industrial CT scanners from Belgium (1 participant), Denmark (7 participants), Germany (11 participants), Italy (1 participant), Japan (1 participant), Singapore (1 participant), UK (4 participants) and USA (2 participants) took part in the comparison. A map showing the locations of the participants is given in Figure 2 and an overview of the participants in alphabetic order is given in Table 1. The order of the participants in Table 1 is not related to the personal identification numbers provided separately by the coordinator.

Note: Compared to the original list [Technical Protocol], one participant has withdrawn and three new participants have joined the comparison.

Figure 2: The 27 participants in the CIA-CT circulation.

Table 1: List of the participants in the circulation in alphabetic order.

Participant	Country
3D-CT A/S	Denmark
BAM Federal institute for materials research and testing	Germany
Braun GmbH, Precision Measurement , CAQ-Engineering	Germany
Carl Zeiss IMT GmbH	Germany
Danish Technological Institute (DTI)	Denmark
Fraunhofer Development Center for X-ray Technology (EZRT)	Germany
GE Measurement & Control (Zebicon A/S)	Denmark
GRUNDFOS A/S	Denmark
Hexagon Metrology Inc	USA
Huddersfield University (HUD)	UK
Institute of Manufacturing Metrology, Friedrich-Alexander-University Erlangen-Nuremberg (FMT)	Germany
Katholieke Universiteit Leuven	Belgium
LEGO System A/S	Denmark
National Metrology Institute of Japan, National Inst. of Adv. Ind. Science and Technology (AIST)	Japan
National Physical Laboratory (NPL)	UK
Nikon Metrology UK	UK
Novo Nordisk A/S, Device R&D	Denmark
Novo Nordisk A/S, DMS Metrology & Calibration	Denmark
SGS Institut Fregenius GmbH	Germany
SIMTech	Singapore
UNCC, Center for Precision Metrology	USA
University of Padova (UNIPD)	Italy
University of Southampton	UK
Wenzel Volumetrik GmbH	Germany
Werth Messtechnik GmbH	Germany
Mikroproduktionstechnik, Fraunhofer-Inst. f. Produktionsanlagen u. Konstruktionstechnik (IPK)	Germany
YXLON International GmbH	Germany

1.4. Items

Two items were used, selected among common industrial parts: a polymer part (Item 1) and a metal part (Item 2). Item 1 is a polymer brick from LEGO. The item is made of Acrylonitrile Butadiene Styrene (ABS) featuring eight knobs in one row. Item 2 is a metallic tubular component from the medical industry. The two items are considered more similar to industrial parts commonly measured in industry, in terms of material, dimensions and geometrical properties, than reference artefacts commonly used for calibration and verification of CT scanners. The two items are shown in Figure 3. The items are contained in a box. Pictures of the box and the items can be seen in Figure 4. All together, 30 Item 1 pieces and 29 Item 2 pieces were manufactured and measured at CGM. 27 sets were circulated.

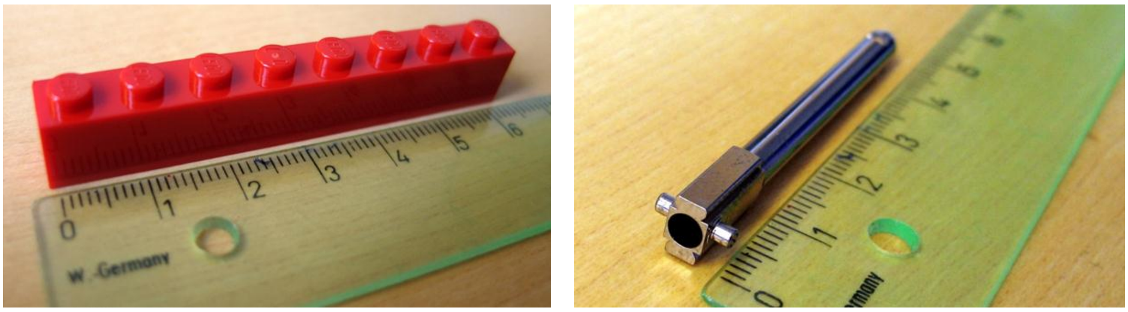


Figure 3: Item 1 (left) and Item 2 (right).

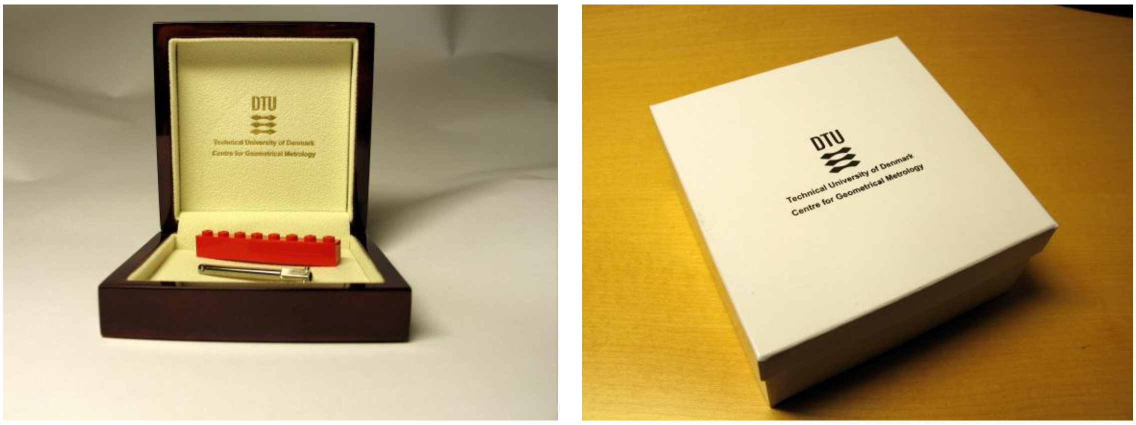


Figure 4: Internal box containing the two items (left) and external box for storage and transportation of the items (right).

2. Measurement procedures

The participants were responsible for following measurement procedures and instructions prepared by the project coordinator [Technical Protocol] and distributed by email before starting the circulation. The protocol includes documents which should be filled out (Templates shown in the Appendix at the end of this report). The selection of CT scanning parameters was left to the participants' choice, to avoid limitation of their capabilities, and because it was impossible to specify the scanning parameters, when different CT scanners were involved in the comparison.

A presentation of the items, measurements details, datums to be used, and measurands can be found in [Technical Protocol], and is summarized in Table 2, Table 3, Figure 5 and Figure 6. The selected geometrical features were length, diameter and roundness.

Table 2: Item 1 – Overview of measurands; D1, R1 and L1.

Identification		Description
Diameter,	*D1*	Diameter of knob at inlet *D1* - circle (GG) is measured 1 mm above datum A
Roundness,	*R1*	Roundness of knob at inlet *R1* - circle (LSCI) is measured 1 mm above datum A
Length,	*L1*	Distance between datum B and datum C 1 mm above datum A

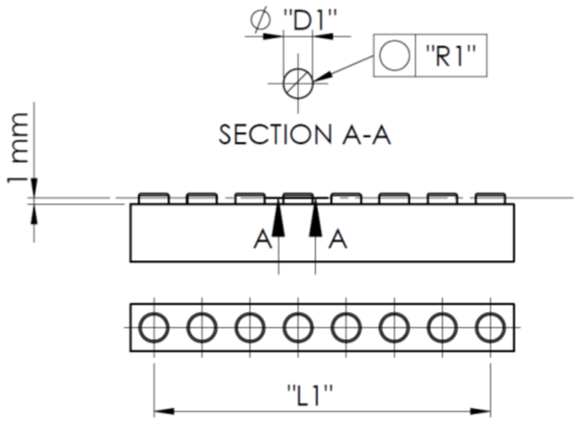


Figure 5: Item 1 – Overview of measurands; D1, R1 and L1.

Table 3: Item 2 – Overview of measurands; D1, R1, D2, R2 and L1.

Identification		**Description**
Diameter,	*D1*	Internal diameter, least square fitting (GG) *D1* – circle is measured 2 mm from datum B
Roundness,	*R1*	Roundness of internal diameter *R1* – on circle (LSCI) is measured 2 mm from datum B
Diameter,	*D2*	Internal diameter , least square fitting (GG) *D2* – circle is measured 12 mm from datum B
Roundness,	*R2*	Roundness of internal diameter *R2* – on circle (LSCI) is measured 12 mm from datum B
Length,	*L1*	Total length L1 - The length between the two “GG” planes, in the axis of the primary alignment (in the centre axis of the item – intersection between axis and planes)

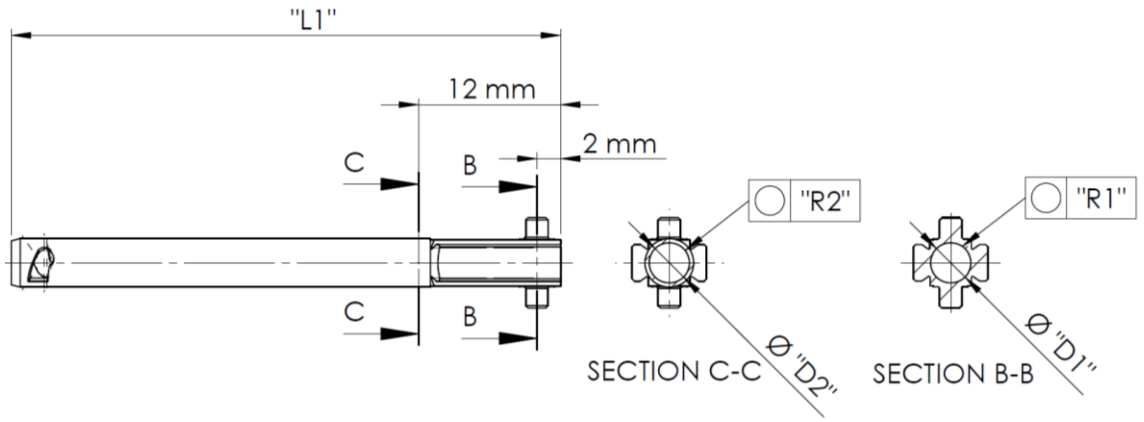


Figure 6: Item 2 – Overview of measurands; D1, R1, D2, R2 and L1.

3. Reference values

Reference values are presented in [Reference Measurements].

All the items were measured by the coordinator using coordinate measuring machines before and after circulation.

Figure 1: CMMs of the type UPMC 850 CARAT (left) and Zeiss OMC 850 (right) placed at CGM.

Stability of the items was documented through comparison of measurements before and after the circulation. Both items have shown a good stability through the approx. 6 months circulation.

The calculated reference values and their corresponding uncertainties are shown in Table 4 and Table 5.

Table 4: Item 1 – Reference values and their corresponding expanded uncertainties (k=2). Values are in mm.

	Diameter *D1*		Roundness *R1*		Length *L1*	
ID no.	Y	U	Y	U	Y	U
1	4.9026	0.0022	0.0040	0.0018	55.9134	0.0055
2	4.9043	0.0015	0.0040	0.0023	55.9515	0.0055
3	4.9024	0.0014	0.0035	0.0018	55.9437	0.0055
4	4.9043	0.0015	0.0038	0.0020	55.9484	0.0055
5	4.9041	0.0013	0.0050	0.0018	55.9518	0.0055
6	4.9004	0.0012	0.0038	0.0019	55.9530	0.0055
7	4.9045	0.0015	0.0039	0.0021	55.9539	0.0054
8	4.9038	0.0023	0.0051	0.0027	55.9114	0.0055
9	4.9026	0.0023	0.0041	0.0019	55.9168	0.0055
10	4.9043	0.0016	0.0048	0.0046	55.9551	0.0055
11	4.9020	0.0021	0.0043	0.0032	55.9455	0.0055
12	4.9028	0.0023	0.0044	0.0022	55.9134	0.0055
13	4.9027	0.0014	0.0035	0.0018	55.9492	0.0055
14	4.9027	0.0014	0.0034	0.0018	55.9476	0.0055
15	4.9042	0.0015	0.0034	0.0018	55.9573	0.0054
16	4.9046	0.0016	0.0039	0.0024	55.9599	0.0055
17	4.9041	0.0019	0.0049	0.0019	55.9511	0.0055
18	4.9041	0.0014	0.0062	0.0027	55.9534	0.0055
19	4.9008	0.0011	0.0042	0.0025	55.9524	0.0055
20	4.9006	0.0012	0.0037	0.0020	55.9525	0.0055
21	4.9038	0.0019	0.0050	0.0018	55.9475	0.0055
22	4.9009	0.0011	0.0036	0.0039	55.9543	0.0056
23	4.9044	0.0013	0.0050	0.0018	55.9529	0.0055
24	4.9045	0.0016	0.0036	0.0018	55.9601	0.0055
25	4.9023	0.0012	0.0042	0.0023	55.9530	0.0056
26	4.9043	0.0019	0.0048	0.0018	55.9493	0.0055
27	4.9045	0.0019	0.0045	0.0018	55.9508	0.0055
28	4.9045	0.0015	0.0038	0.0020	55.9482	0.0053
29	4.9019	0.0020	0.0041	0.0020	55.9416	0.0055
30	4.9026	0.0014	0.0045	0.0021	55.9455	0.0055
AVG		0.0016		0.0022		0.0055
MAX		0.0023		0.0046		0.0056
MIN		0.0011		0.0018		0.0053

Table 5: Item 2 –Reference values and their corresponding expanded uncertainties (k=2). Values are in mm.

	Diameter *D1*		Roundness *R1*		Diameter *D2*		Roundness *R2*		Length *L1*	
ID no.	Y	U	Y	U	Y	U	Y	U	Y	U
1	3.4018	0.0014	0.0041	0.0008	3.4054	0.0009	0.0082	0.0010	46.3555	0.0021
2	3.4026	0.0010	0.0035	0.0028	3.3974	0.0011	0.0550	0.0016	46.3650	0.0027
3	3.4193	0.0020	0.0049	0.0064	3.4073	0.0020	0.0047	0.0015	46.3480	0.0030
4	3.4068	0.0019	0.0059	0.0008	3.4066	0.0011	0.0061	0.0013	46.3554	0.0015
5	3.4027	0.0015	0.0035	0.0009	3.4018	0.0010	0.0070	0.0011	46.3978	0.0037
6	3.4003	0.0011	0.0035	0.0015	3.4050	0.0013	0.0072	0.0021	46.3392	0.0022
7	3.4001	0.0019	0.0039	0.0036	3.4034	0.0029	0.0071	0.0010	46.3567	0.0010
8	3.4025	0.0013	0.0037	0.0019	3.4025	0.0017	0.0069	0.0010	46.3551	0.0039
9	3.4032	0.0021	0.0038	0.0044	3.4035	0.0034	0.0064	0.0012	46.3711	0.0015
10	3.4024	0.0021	0.0039	0.0030	3.4044	0.0024	0.0080	0.0015	46.3484	0.0033
11	3.4037	0.0026	0.0049	0.0019	3.4065	0.0017	0.0081	0.0011	46.3628	0.0026
12	3.4012	0.0010	0.0039	0.0011	3.4036	0.0013	0.0061	0.0020	46.3625	0.0035
13	3.4039	0.0018	0.0045	0.0011	3.4057	0.0019	0.0088	0.0034	46.3619	0.0052
14	3.4025	0.0018	0.0040	0.0034	3.4032	0.0011	0.0083	0.0009	46.3636	0.0022
15	3.4022	0.0008	0.0038	0.0013	3.4044	0.0014	0.0070	0.0011	46.3551	0.0025
16	3.4087	0.0011	0.0068	0.0006	3.4066	0.0009	0.0076	0.0032	46.3493	0.0012
17	3.4027	0.0019	0.0049	0.0024	3.4081	0.0020	0.0063	0.0012	46.3600	0.0023
18	3.4055	0.0016	0.0046	0.0024	3.4063	0.0021	0.0074	0.0020	46.3427	0.0020
19	3.4072	0.0023	0.0046	0.0010	3.4073	0.0011	0.0088	0.0011	46.3371	0.0030
20	3.4075	0.0014	0.0043	0.0041	3.4095	0.0012	0.0080	0.0016	46.3510	0.0032
21	3.3999	0.0019	0.0036	0.0032	3.4093	0.0026	0.0129	0.0023	46.3826	0.0039
22	3.3965	0.0013	0.0043	0.0009	3.3983	0.0011	0.0120	0.0022	46.3681	0.0017
23	3.4098	0.0012	0.0048	0.0022	3.4091	0.0019	0.0121	0.0023	46.3815	0.0018
24	3.3977	0.0011	0.0055	0.0011	3.4028	0.0011	0.0127	0.0012	46.3780	0.0017
25	3.3993	0.0010	0.0038	0.0036	3.4041	0.0028	0.0118	0.0013	46.3794	0.0016
26	3.4041	0.0009	0.0034	0.0013	3.4096	0.0013	0.0121	0.0008	46.3848	0.0017
27	3.3999	0.0010	0.0063	0.0011	3.4029	0.0012	0.0116	0.0008	46.3766	0.0027
28	3.3914	0.0008	0.0041	0.0024	3.3979	0.0008	0.0124	0.0014	46.3709	0.0026
29	3.3957	0.0014	0.0052	0.0012	3.4060	0.0017	0.0105	0.0020	46.3789	0.0027
AVG		0.0015		0.0021		0.0016		0.0016		0.0025
MAX		0.0026		0.0064		0.0034		0.0034		0.0052
MIN		0.0008		0.0006		0.0008		0.0008		0.0010

Analysis of participants' data

The measurements carried out by the participants on the industrial CT scanners are presented and their data analyses illustrated in this chapter. Not all participants have measured all measurands on both items.

3.1. Measurements carried out by participants

Information on set-up data is provided in the Measurement Report for each item, with the main subjects shown in Table 6.

Table 6: Main subjects in the Measurement Report.

GENERAL INFORMATION
CT SCANNER
SOFTWARE
SETUP AND SCANNING
PROCESSING PARAMETERS
UNCERTAINTY ASSESSMENT
ATTACHMENTS

Participant's results are presented in the following. Analyses were performed for the following subjects:

- Main results for Item 1.
- Main results for Item 2.
- Agreement between participant results and reference measurements.
- Involved industrial CT scanners by the participants.
- Applied software by the participants.
- Impact of instrument settings and operator.
- Applied uncertainties by the participants.

3.2. Main results for Item 1

Participants' values and their corresponding uncertainties are shown in Table 7, Table 8 and Table 9.

Main results are shown for diameter, roundness and length in Figure 7, Figure 8 and Figure 9.

For both diameter *D1* and roundness *R1*, Figure 7 and Figure 8 show that the applied filters have no major effect on the results. In the following, results are only treated for the unfiltered data.

In Figure 7, there is a good agreement between most participants' results and the reference values, except for no 10 and 17 that show a bad agreement, which could be due to measurement errors as threshold determination, non-corrected scale and/or temperature corrections. It appears that participant no 27 has overestimated their uncertainty compared to the other participants. An average uncertainty on 6.6 µm (neglecting the estimate from no 27) was stated by the participants for *D1*.

There is a trend for the case of roundness in Figure 8, where the roundness measured by the participants is higher than the unfiltered reference value. It is clear that form measurements are more problematic compared to size measurements because form measurements are more affected by the influence of scatter and noise of CT data [Carmignato et al., 2011]. An average uncertainty on 10.6 µm was stated by the participants for *R1*.

In Figure 9, there is a good agreement between most participants' results and the reference values, except for no 10 that show a bad agreement, which could be due to measurement errors as non-corrected scale and/or temperature corrections. It was again detected that participant no 27 has overestimated their uncertainty compared to the other participants. An average uncertainty on 11.2 µm (neglecting the estimate from no 27) was stated by the participants for *L1*.

It was detected that participant no 27 has overestimated their uncertainties for length and diameter for Item 1.

Table 7: Item 1, D1 – Participants' values and their corresponding uncertainties. Values are in mm.

	Diameter *D1 - unfiltered*		Diameter *D1 - 50 UPR*		Diameter *D1 - 150 UPR*	
ID no.	Y	U	Y	U	Y	U
1	4.9017	0.0091	4.9017	0.0091	4.9017	0.0091
2	4.9060	0.0070	N/A	N/A	N/A	N/A
3	4.9100	N/A	N/A	N/A	N/A	N/A
4	4.8960	0.0015	N/A	N/A	N/A	N/A
5	4.9080	N/A	4.9080	N/A	4.9080	N/A
6	4.8980	0.0064	4.8980	0.0064	4.8980	0.0064
7	4.9034	0.0091	N/A	N/A	N/A	N/A
8	4.8930	0.0030	N/A	N/A	N/A	N/A
9	4.9010	0.0046	4.9010	0.0046	4.9010	0.0046
10	4.9730	0.0020	N/A	N/A	N/A	N/A
11	4.9040	0.0020	4.9040	0.0020	4.9040	0.0020
12	4.9036	0.0093	4.9036	0.0093	4.9036	0.0093
13	4.9020	0.0050	N/A	N/A	N/A	N/A
14	4.9020	0.0020	4.8998	0.0020	4.8998	0.0020
15						
16						
17	5.1837	0.0112	5.1837	0.0084	5.1837	0.0112
18	4.9050	0.0070	N/A	N/A	N/A	N/A
19	4.9020	0.0000	4.9030	0.0000	4.9030	0.0010
20	4.9014	0.0050	4.9013	0.0050	N/A	N/A
21	4.9136	0.0057	N/A	N/A	N/A	N/A
22	4.9003	0.0204	4.9003	0.0204	4.9003	0.0204
23	4.9076	0.0080	4.9076	0.0080	4.9076	0.0080
24	4.9060	0.0080	4.9060	0.0080	4.9060	0.0080
25	4.9018	0.0090	N/A	N/A	N/A	N/A
26	4.9030	N/A	N/A	N/A	N/A	N/A
27	4.9080	0.1072	4.9070	0.1072	4.9070	0.1072
28	4.9014	0.0090	N/A	N/A	N/A	N/A
AVG		0.0109		0.0146		0.0158
MAX		0.1072		0.1072		1.1072
MIN		0.0000		0.0000		0.0010

Table 8: Item 1, R1 – Participants' values and their corresponding uncertainties. Values are in mm.

	Roundness *R1 - unfiltered*		Roundness *R1 - 50 UPR*		Roundness *R1 - 150 UPR*	
ID no.	Y	U	Y	U	Y	U
1	0.0129	0.0090	0.0102	0.0090	0.0129	0.0090
2	0.0150	N/A	N/A	N/A	N/A	N/A
3	N/A	N/A	N/A	N/A	N/A	N/A
4	0.0150	0.0015	N/A	N/A	N/A	N/A
5	0.0200	N/A	0.0110	N/A	0.0180	N/A
6	0.0180	0.0146	0.0140	0.0108	0.0180	0.0146
7	0.0166	0.0090	N/A	N/A	N/A	N/A
8	0.0300	0.0100	N/A	N/A	N/A	N/A
9	0.0200	0.0045	0.0140	0.0045	0.0180	0.0045
10	0.0390	0.0080	N/A	N/A	N/A	N/A
11	0.0110	0.0020	0.0090	0.0030	0.0110	0.0030
12	0.0173	0.0046	0.0143	0.0046	0.0173	0.0046
13	0.0390	0.0400	0.0270	0.0300	N/A	N/A
14	0.0076	N/A	0.0125	N/A	0.0175	N/A
15						
16						
17	0.0151	0.0112	0.0101	0.0088	0.0133	0.0116
18	0.0160	0.0110	N/A	N/A	N/A	N/A
19	0.0230	0.0070	0.0160	0.0050	0.0210	0.0040
20	0.0215	0.0215	0.0156	0.0156	N/A	N/A
21	0.0201	0.0015	0.0409	0.0112	0.1031	0.0112
22	0.0125	0.0180	0.0099	0.0180	0.0125	0.0180
23	0.0143	0.0080	0.0098	0.0080	0.0143	0.0080
24	0.0150	0.0130	0.0120	0.0130	0.0080	0.0130
25	0.0106	0.0090	N/A	N/A	N/A	N/A
26	0.0210	N/A	N/A	N/A	N/A	N/A
27	0.0120	0.0092	0.0120	0.0092	0.0120	0.0092
28	0.0131	0.0090	N/A	N/A	N/A	N/A
AVG		0.0106		0.0108		0.0092
MAX		0.0400		0.0300		0.0180
MIN		0.0015		0.0030		0.0030

Table 9: Item 1, L1 – Participants' values and their corresponding uncertainties. Values are in mm.

	Length *L1*	
ID no.	Y	U
1	55.9073	0.0101
2	55.9450	0.0070
3	56.0100	N/A
4	55.8230	0.0015
5	55.9610	N/A
6	55.9585	0.0190
7	55.9454	0.0101
8	55.7940	0.0110
9	55.9310	0.0052
10	56.7150	0.0170
11	55.9400	0.0050
12	55.9085	0.0105
13	55.9730	0.0120
14	55.9279	0.0030
15		
16		
17	55.9960	0.0093
18	55.9730	0.0170
19	55.9360	0.0020
20	55.9490	0.0080
21	55.9612	0.0223
22	55.9549	0.0204
23	55.9551	0.0080
24	55.9490	0.0180
25	55.9548	0.0100
26	55.9600	N/A
27	55.6860	1.1227
28	55.8849	0.0200

AVG		0.0595
MAX		1.1227
MIN		0.0015

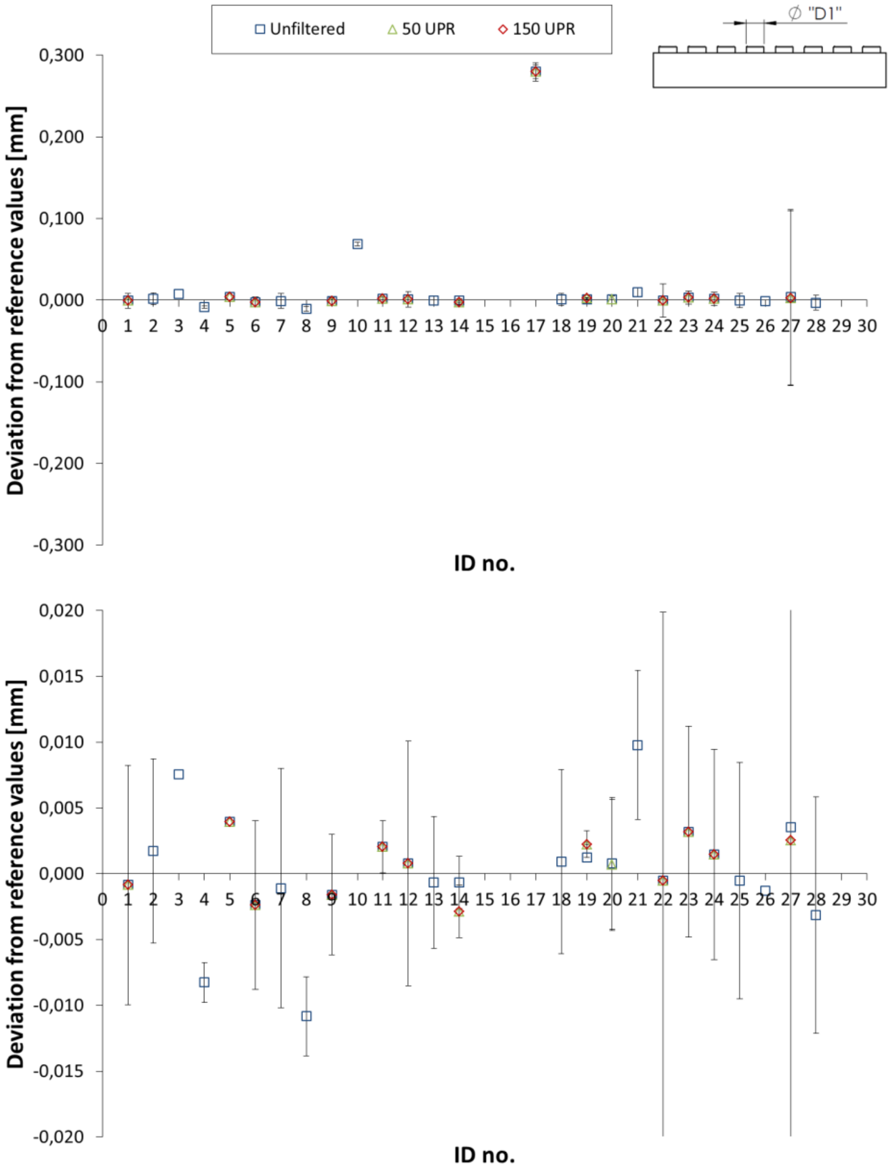


Figure 7: Results for Item 1. Diameter D1 unfiltered, 50 UPR and 150 UPR. Top: deviation range ± 0.30 mm. Bottom: deviation range ± 0.02 mm

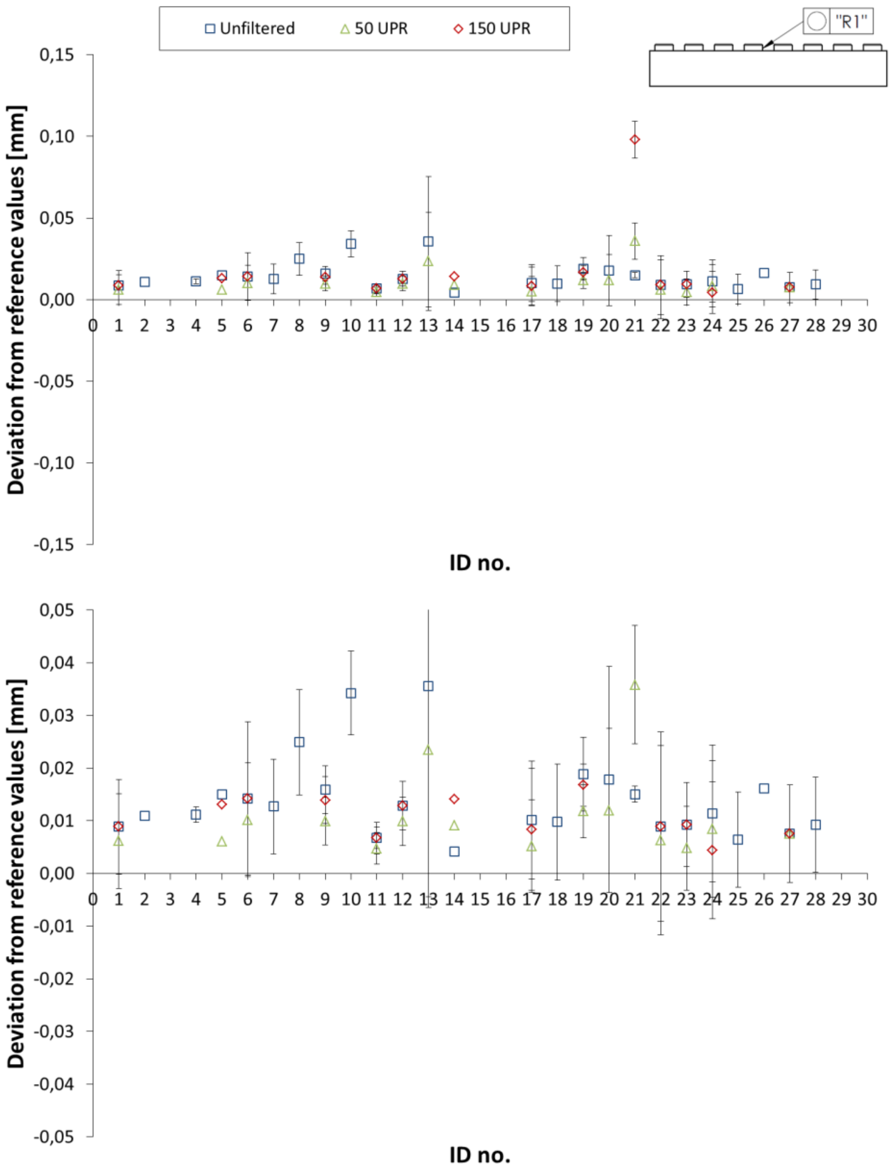


Figure 8: Results for Item 1. Roundness R1 unfiltered, 50 UPR and 150 UPR. Top: deviation range ± 0.15 mm. Bottom: deviation range ± 0.05 mm

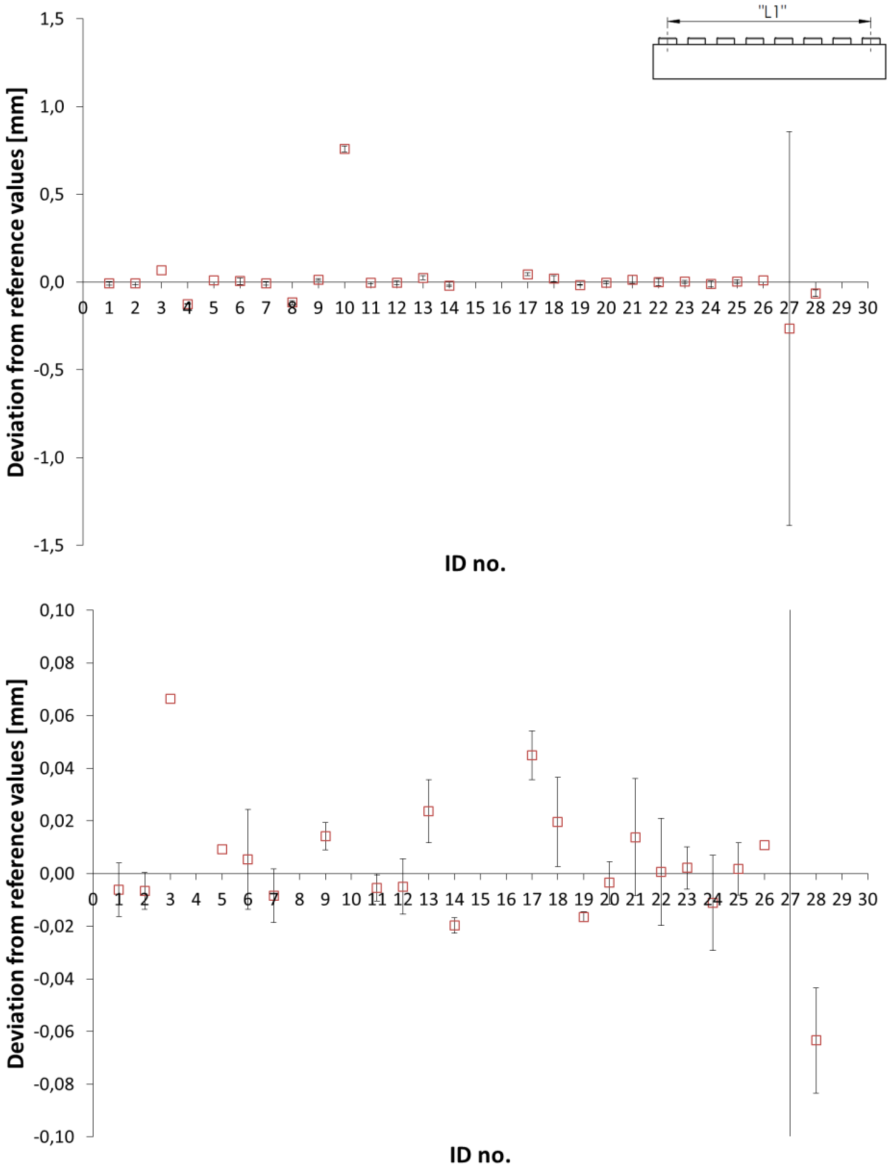


Figure 9: Results for Item 1. Length L1. Top: deviation range ± 1.50 mm. Bottom: deviation range ± 0.10 mm.

3.3. Main results for Item 2

Participants' values and their corresponding uncertainties are shown in Table 10, Table 11, Table 12, Table 13 and Table 14.

Main results are shown for diameter, roundness and length in Figure 10, Figure 11, Figure 12, Figure 13 and Figure 14.

For both diameter *D1* and *D2*, and roundness *R1* and *R2*, Figure 10, Figure 11, Figure 12 and Figure 13 show that the applied filters have no major effect on the results. In the following, results are only treated for the unfiltered data.

In Figure 10, there is a good agreement between most participants' results and the reference values, except for no 17 that show a big deviation from the unfiltered reference value, which could be due to measurement errors as threshold determination, non-corrected scale and/or temperature corrections. It appears that participant no 17 and 27 have overestimated their uncertainty compared to the other participants. An average uncertainty on 9.6 µm (neglecting the estimates from no 17 and 27) was stated by the participants for *D1*.

There is a trend for the case of roundness *R1* in Figure 11, where the roundness measured by the participants is higher than the unfiltered reference value. It appears that participant no 17 has overestimated their uncertainty compared to the other participants. An average uncertainty on 20.1 µm (neglecting the estimates from no 17) was stated by the participants for *R1*.

In Figure 12, there is a good agreement between most participants' results and the reference values, except for no 1, 17 and 21 that show a big deviation from the unfiltered reference value, which could be due to measurement errors as threshold determination, non-corrected scale and/or temperature corrections. It appears that participant no 10 and 27 have overestimated their uncertainty compared to the other participants. An average uncertainty on 7.5 µm (neglecting the estimates from no 10 and 27) was stated by the participants for *D2*.

The same trend was detected for *R2* as for *R1* for the case of roundness in Figure 13, where the roundness measured by the participants is higher than the unfiltered reference value. It appears that participant no 17 has overestimated their uncertainty compared to the other participants. An average uncertainty on 10.8 µm (neglecting the estimates from no 17) was stated by the participants for *R2*. Furthermore it appears that deviation from the unfiltered value increases in the case of roundness if the wall thickness increases, see Figure 15. This statement is valid for all participants except no 3 and 7. This may be due to the influence of scatter and noise of CT data, and the thicker wall producing higher attenuation of the X-rays. The wall thickness for *R1* is thicker compared to *R2*.

In Figure 14, there is a good agreement between most participants' results and the reference values, except for no 10 and 21 that show a bad agreement, which could be due to measurement errors as threshold determination, non-corrected scale and/or temperature corrections. It was again detected that participant no 27 has overestimated their uncertainty compared to the other participants. An average uncertainty on 12.0 µm (neglecting the estimate from no 27) was stated by the participants for *L1*.

It was detected that participant no 27 has overestimated their uncertainties for length and diameters for Item 2.

Table 10: Item 2, D1 – Participants' values and their corresponding uncertainties. Values are in mm.

	Diameter *D1 - unfiltered*		Diameter *D1 - 50 UPR*		Diameter *D1 - 150 UPR*	
ID no.	Y	U	Y	U	Y	U
1	3.3722	0.0091	3.3722	0.0091	3.3722	0.0091
2	3.3840	0.0050	N/A	N/A	N/A	N/A
3	3.3900	N/A	N/A	N/A	N/A	N/A
4	N/A	N/A	N/A	N/A	N/A	N/A
5	3.3980	N/A	3.3970	N/A	3.3970	N/A
6	3.3940	0.0088	3.3940	0.0088	3.3940	0.0088
7	3.3884	0.0091	N/A	N/A	N/A	N/A
8	3.3610	0.0020	N/A	N/A	N/A	N/A
9	3.4020	0.0045	3.4020	0.0045	3.4020	0.0045
10	3.4130	0.0232	N/A	N/A	N/A	N/A
11	3.4090	0.0020	3.4090	0.0020	3.4090	0.0020
12	3.3866	0.0093	3.3866	0.0093	3.3866	0.0093
13	3.3920	0.0160	N/A	N/A	N/A	N/A
14	3.3728	0.0030	3.3730	0.0030	3.3730	0.0030
15						
16						
17	3.5843	0.4304	3.5843	0.4236	3.5843	0.4288
18	3.4110	0.0070	N/A	N/A	N/A	N/A
19	3.4050	0.0010	3.4050	0.0010	3.4090	0.0010
20	N/A	N/A	N/A	N/A	N/A	N/A
21	3.4265	0.0069	N/A	N/A	N/A	N/A
22	3.3781	0.0350	3.3781	0.0350	3.3781	0.0350
23	3.4056	0.0080	3.4056	0.0080	3.4056	0.0080
24	3.3952	0.0087	3.3952	0.0087	3.3952	0.0087
25	3.3778	0.0090	N/A	N/A	N/A	N/A
26	3.3970	N/A	N/A	N/A	N/A	N/A
27	3.3890	0.0768	3.3890	0.0768	3.3890	0.0768
28	3.3835	0.0150	N/A	N/A	N/A	N/A

AVG		0.0328		0.0491		0.0496
MAX		0.4304		0.4236		0.4288
MIN		0.0010		0.0010		0.0010

Table 11: Item 2, R1 – Participants' values and their corresponding uncertainties. Values are in mm.

	Roundness *R1 - unfiltered*		Roundness *R1 - 50 UPR*		Roundness *R1 - 150 UPR*	
ID no.	Y	U	Y	U	Y	U
1	0.1601	0.0090	0.1601	0.0090	0.1601	0.0090
2	0.0580	N/A	N/A	N/A	N/A	N/A
3	0.0524	N/A	N/A	N/A	N/A	N/A
4	N/A	N/A	N/A	N/A	N/A	N/A
5	0.0240	N/A	0.0140	N/A	0.0180	N/A
6	0.0320	0.0293	0.0250	0.0253	0.0290	0.0293
7	0.0250	N/A	N/A	N/A	N/A	N/A
8	0.0510	0.0050	N/A	N/A	N/A	N/A
9	0.0150	0.0045	0.0160	0.0045	0.0170	0.0045
10	0.0720	0.0104	N/A	N/A	N/A	N/A
11	0.0120	0.0020	0.0110	0.0030	0.0130	0.0030
12	0.0582	0.0046	0.0574	0.0046	0.0582	0.0046
13	0.0480	0.0500	N/A	N/A	N/A	N/A
14	0.0077	N/A	0.0117	N/A	0.0249	N/A
15						
16						
17	0.3647	0.4536	0.3492	0.4480	0.3642	0.4528
18	0.0124	0.0065	N/A	N/A	N/A	N/A
19	0.0180	0.0080	0.0150	0.0070	0.0168	0.0080
20	N/A	N/A	N/A	N/A	N/A	N/A
21	0.1003	0.0509	0.0880	0.0107	0.2228	0.1281
22	0.1125	0.1020	0.1125	0.1020	0.1125	0.1020
23	0.0218	0.0080	0.0187	0.0080	0.0218	0.0080
24	0.0200	0.0099	0.0180	0.0099	0.0120	0.0099
25	0.0343	0.0090	N/A	N/A	N/A	N/A
26	0.0330	N/A	N/A	N/A	N/A	N/A
27	0.1380	0.0118	0.1160	0.0113	0.1380	0.0118
28	0.0276	0.0200	N/A	N/A	N/A	N/A
AVG		0.0441		0.0536		0.0643
MAX		0.4536		0.4480		0.4528
MIN		0.0020		0.0030		0.0030

Table 12: Item 2, D2 – Participants' values and their corresponding uncertainties. Values are in mm.

	Diameter *D2 - unfiltered*		Diameter *D2 - 50 UPR*		Diameter *D2 - 150 UPR*	
ID no.	Y	U	Y	U	Y	U
1	3.3161	0.0091	3.3161	0.0091	3.3161	0.0091
2	3.3960	0.0050	N/A	N/A	N/A	N/A
3	3.4000	N/A	N/A	N/A	N/A	N/A
4	N/A	N/A	N/A	N/A	N/A	N/A
5	4.0870	N/A	4.0870	N/A	4.0870	N/A
6	3.4010	0.0053	3.4010	0.0053	3.4010	0.0053
7	3.4064	0.0091	N/A	N/A	N/A	N/A
8	3.3820	0.0020	N/A	N/A	N/A	N/A
9	3.4030	0.0045	3.4030	0.0045	3.4030	0.0045
10	3.4270	0.0394	N/A	N/A	N/A	N/A
11	3.4070	0.0020	3.4070	0.0020	3.4070	0.0020
12	3.4071	0.0093	3.4071	0.0093	3.4071	0.0093
13	3.4050	0.0160	N/A	N/A	N/A	N/A
14	3.3847	0.0030	3.3838	0.0030	3.3841	0.0030
15						
16						
17	3.3716	0.0064	3.3716	0.0052	3.3716	0.0064
18	3.4080	0.0070	N/A	N/A	N/A	N/A
19	3.4080	0.0010	3.4090	0.0010	3.4080	0.0010
20	N/A	N/A	N/A	N/A	N/A	N/A
21	3.4582	0.0030	N/A	N/A	N/A	N/A
22	3.4038	0.0207	3.4038	0.0207	3.4038	0.0207
23	3.4163	0.0080	3.4163	0.0080	3.4163	0.0080
24	3.4039	0.0081	3.4039	0.0081	3.4039	0.0081
25	3.4281	0.0090	N/A	N/A	N/A	N/A
26	3.4280	N/A	N/A	N/A	N/A	N/A
27	3.4060	0.0771	3.4060	0.0771	3.4060	0.0771
28	3.3954	0.0140	N/A	N/A	N/A	N/A

AVG		0.0123		0.0128		0.0129
MAX		0.0771		0.0771		0.0771
MIN		0.0010		0.0010		0.0010

Table 13: Item 2, R2 – Participants' values and their corresponding uncertainties. Values are in mm.

	Roundness *R2 - unfiltered*		Roundness *R2 - 50 UPR*		Roundness *R2 - 150 UPR*	
ID no.	Y	U	Y	U	Y	U
1	0.0432	0.0090	0.0432	0.0090	0.0432	0.0090
2	0.0540	N/A	N/A	N/A	N/A	N/A
3	0.2180	N/A	N/A	N/A	N/A	N/A
4	N/A	N/A	N/A	N/A	N/A	N/A
5	0.0250	N/A	0.0230	N/A	0.0250	N/A
6	0.0180	0.0153	0.0160	0.0124	0.0180	0.0143
7	0.0598	0.0090	N/A	N/A	N/A	N/A
8	0.0520	0.0050	N/A	N/A	N/A	N/A
9	0.0130	0.0045	0.0120	0.0045	0.0130	0.0045
10	0.0070	0.0322	N/A	N/A	N/A	N/A
11	0.0070	0.0020	0.0060	0.0020	0.0070	0.0020
12	0.0137	0.0046	0.0128	0.0046	0.0137	0.0046
13	0.0130	0.0200	N/A	N/A	N/A	N/A
14	0.0005	N/A	0.0068	N/A	0.0100	N/A
15						
16						
17	0.0639	0.0800	0.0618	0.0800	0.0638	0.0800
18	0.0079	0.0045	N/A	N/A	N/A	N/A
19	0.0176	0.0080	0.0160	0.0070	0.0170	0.0080
20	N/A	N/A	N/A	N/A	N/A	N/A
21	0.0306	0.0207	0.0236	0.0180	0.0373	0.0265
22	0.0141	0.0184	0.0141	0.0184	0.0141	0.0184
23	0.0097	0.0080	0.0087	0.0080	0.0097	0.0080
24	0.0130	0.0080	0.0120	0.0080	0.0100	0.0080
25	0.0364	0.0090	N/A	N/A	N/A	N/A
26	0.0300	N/A	N/A	N/A	N/A	N/A
27	0.0090	0.0092	0.0080	0.0092	0.0090	0.0092
28	0.0073	0.0070	N/A	N/A	N/A	N/A

AVG		0.0144		0.0151		0.0160
MAX		0.0800		0.0800		0.0800
MIN		0.0020		0.0020		0.0020

Table 14: Item 2, L1 – Participants' values and their corresponding uncertainties. Values are in mm.

	Length *L1*	
ID no.	Y	U
1	46.3848	0.0099
2	46.3330	0.0050
3	46.4470	N/A
4	N/A	N/A
5	46.3770	N/A
6	46.3680	0.0302
7	46.3587	0.0099
8	46.2850	0.0050
9	46.3180	0.0051
10	46.9370	0.0018
11	46.3920	0.0040
12	46.4083	0.0098
13	46.3730	0.0200
14	46.3681	0.0040
15		
16		
17	46.3908	0.0202
18	46.3730	0.0110
19	46.3300	0.0040
20	N/A	N/A
21	45.7737	0.0011
22	46.3593	0.0270
23	46.3899	0.0080
24	46.3841	0.0296
25	46.3858	0.0100
26	46.4070	N/A
27	46.3870	0.9367
28	46.4108	0.0250

AVG		0.0561
MAX		0.9367
MIN		0.0011

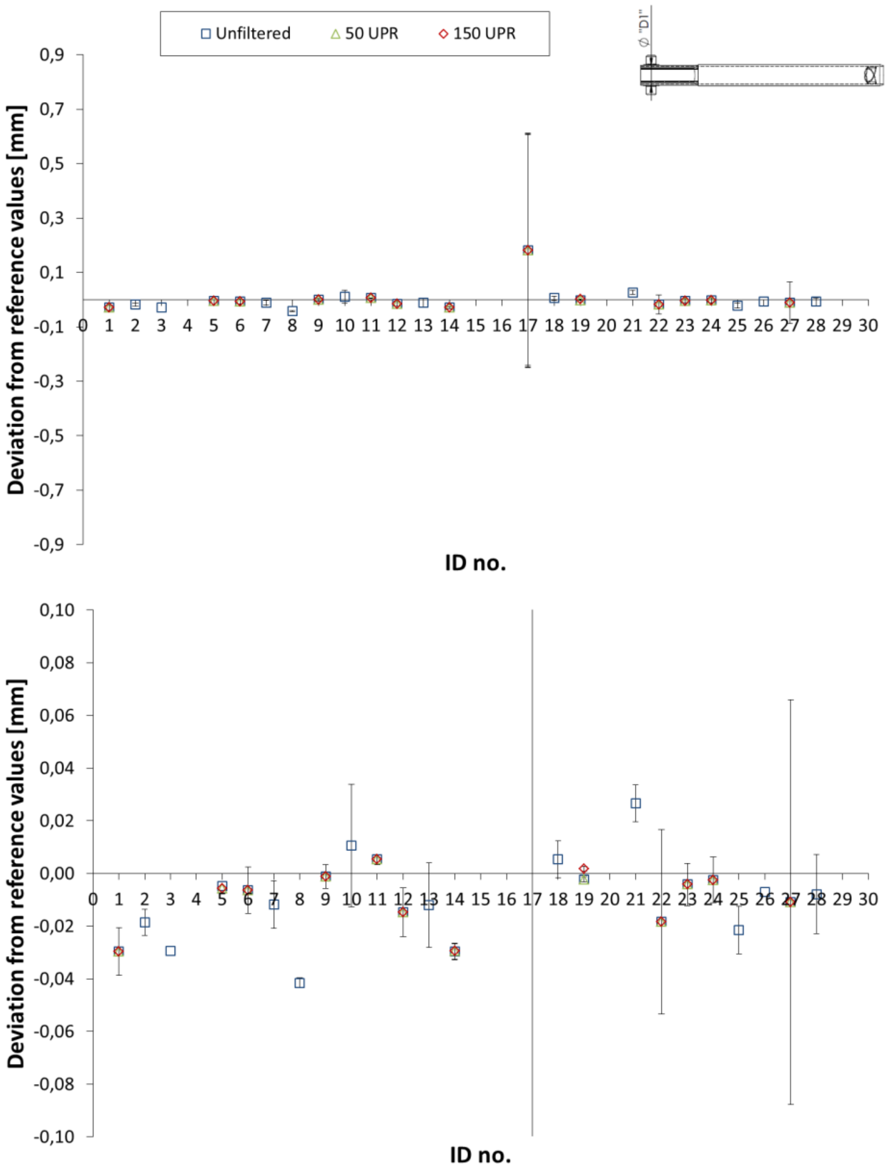


Figure 10: Results for Item 2. Diameter D1. Top: deviation range ± 0.90 mm. Bottom: deviation range ± 0.10 mm.

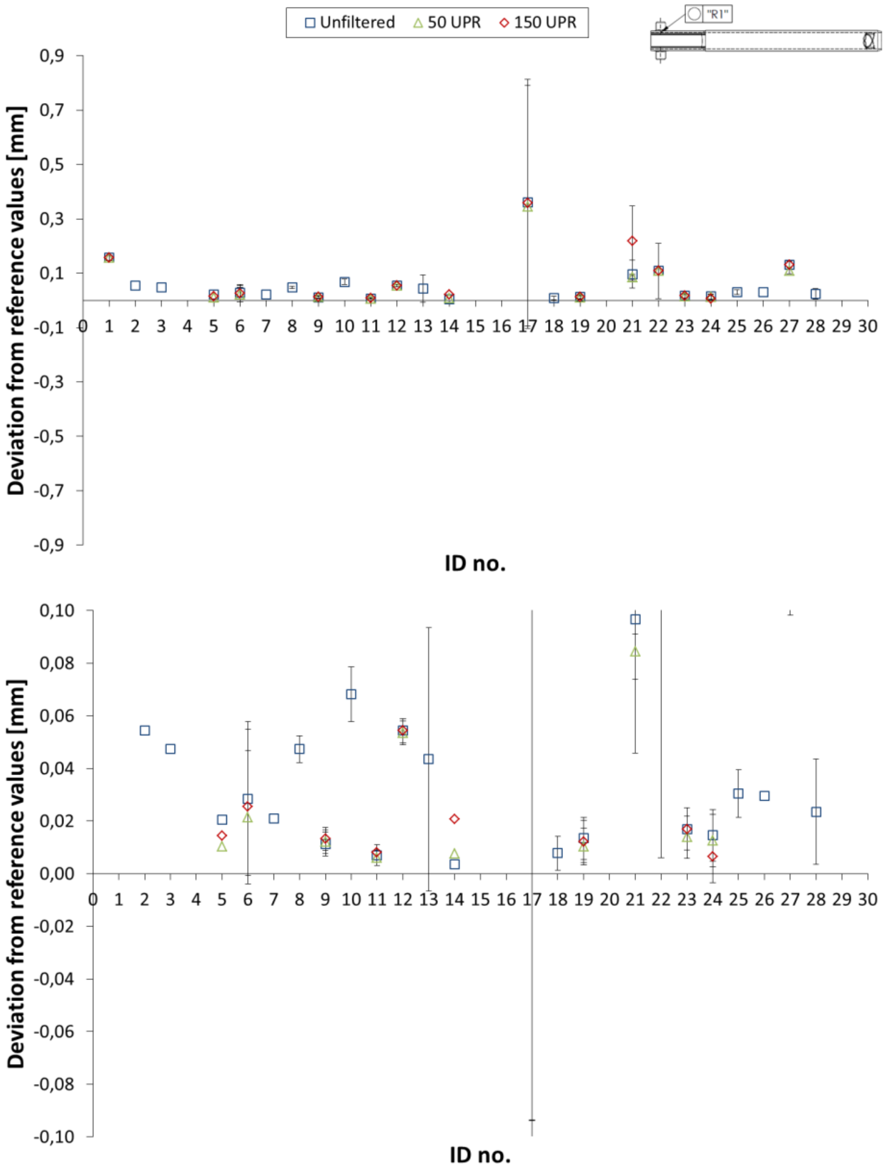


Figure 11: Results for Item 2. Roundness R1. Top: deviation range ± 0.90 mm. Bottom: deviation range ± 0.10 mm.

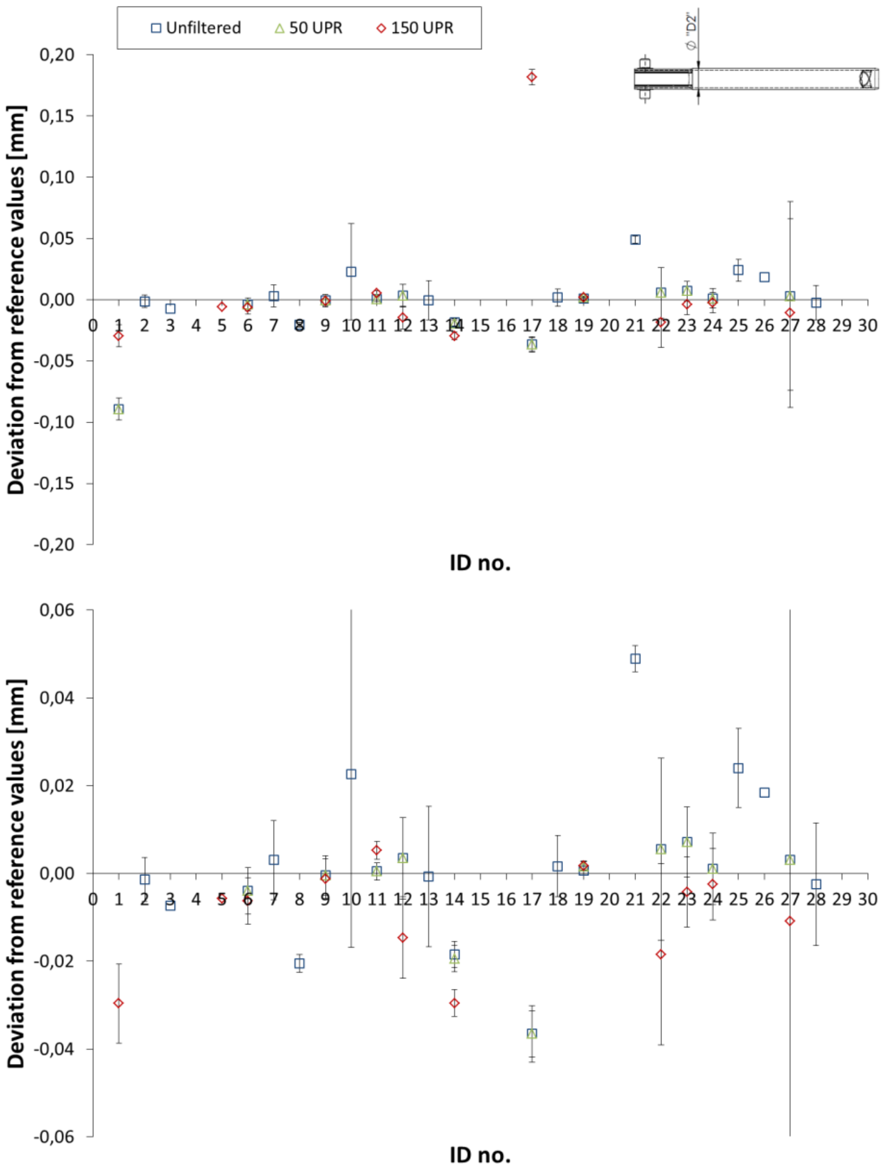


Figure 12: Results for Item 2. Diameter D2. Top: deviation range ± 0.20 mm. Bottom: deviation range ± 0.06 mm.

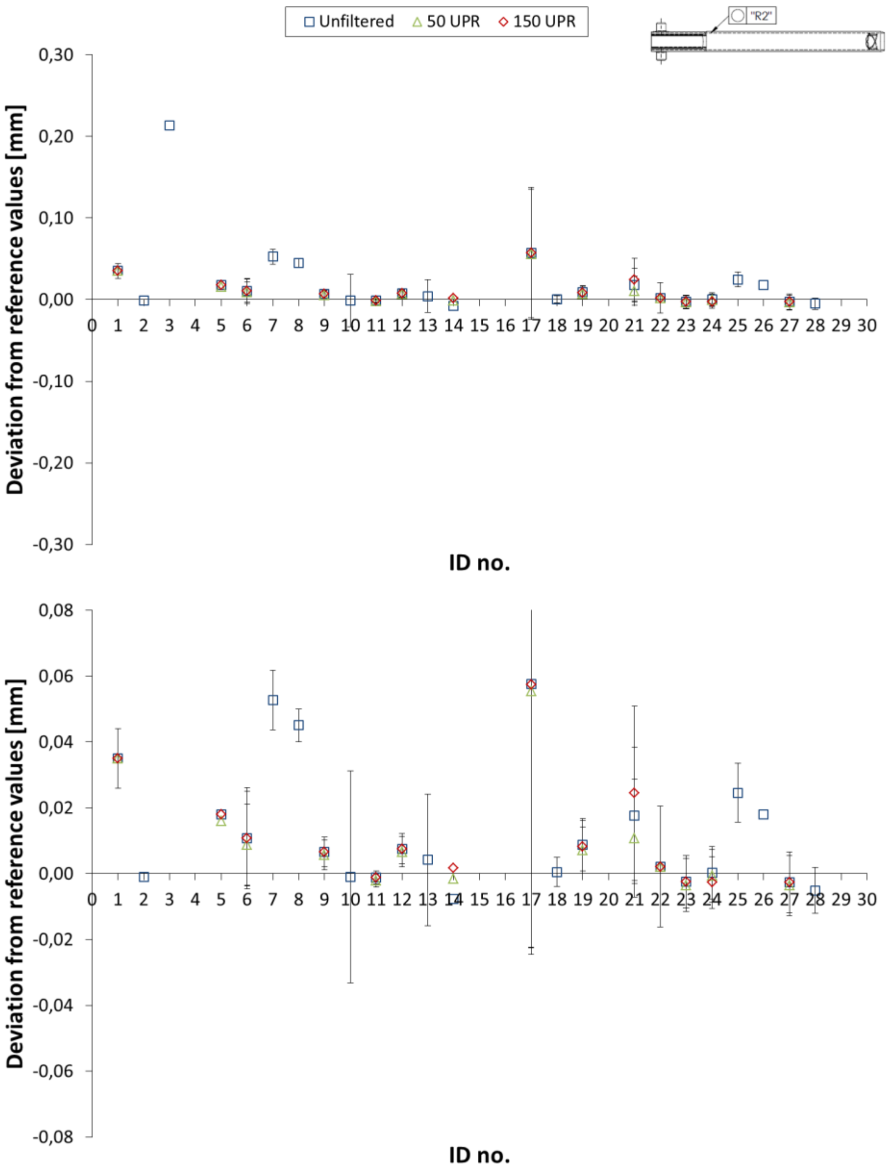


Figure 13: Results for Item 2. Roundness R2. Top: deviation range ± 0.30 mm. Bottom: deviation range ± 0.08 mm.

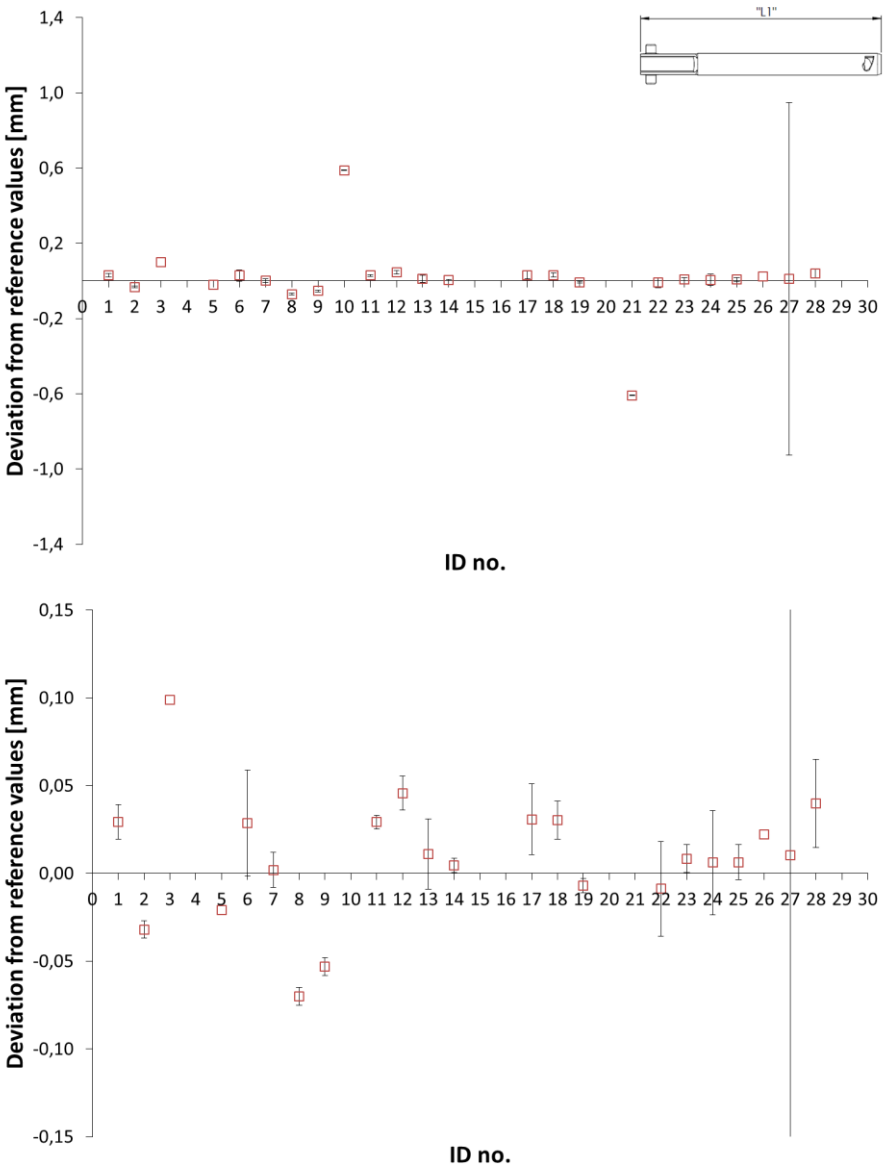


Figure 14: Results for Item 2. Length L1. Top: deviation range ± 1.40 mm. Bottom: deviation range ± 0.15 mm.

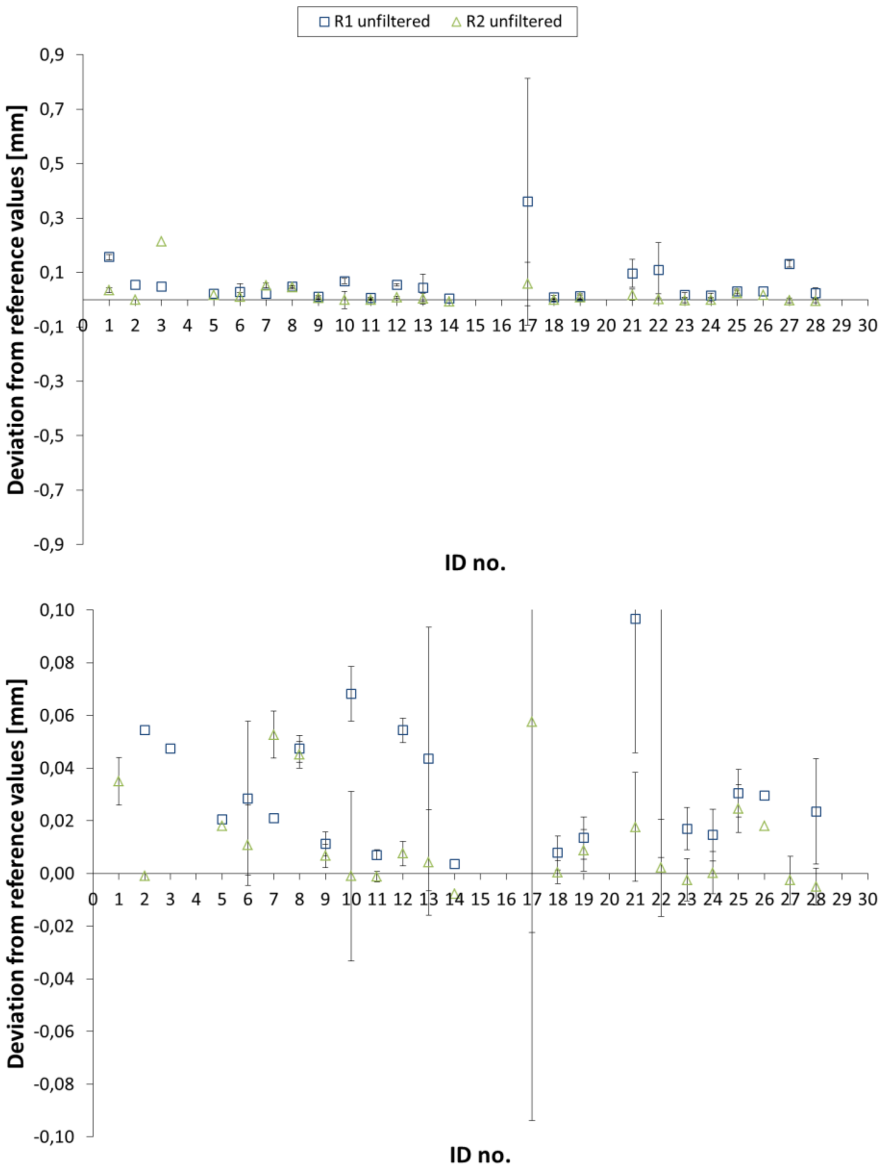


Figure 15: Results for Item 2. Comparing roundness R1 and R2. Top: deviation range ± 0.90 mm. Bottom: deviation range ± 0.10 mm.

3.4. Agreement between participant results and reference measurements

In order to judge the agreement between reference measurements and participant measurements, the E_n value normalised with respect to the stated uncertainty was computed according to ISO guidelines [ISO/IEC 17043, 2010], see Equation 3. If $|E_n| < 1$, agreement between reference measurement results participant results is proven, while it is not the case if $|E_n| \geq 1$.

$$E_n = \frac{x_{lab} - x_{ref}}{\sqrt{U_{lab}^2 + U_{ref}^2}} \tag{3}$$

Here, x_{lab} is the measurement obtained by the participant and x_{ref} the reference value, while U_{lab} and U_{ref} are the corresponding expanded uncertainties.

Disagreement can be caused by systematic errors in the measurement and those related to the uncertainty estimate. Each participant can extract information from the graphs in Figure 7, Figure 8, Figure 9, Figure 10, Figure 11, Figure 12, Figure 13, Figure 14 and Figure 15.

Results from the participants are for both items based on unfiltered results for diameters and roundness. From Figure 16 and Figure 17 it is clear that *R1* for Item 2 is problematic compared to the other measurands. This may be due to the influence of scatter and noise of CT data, and the thicker wall producing higher attenuation of the X-rays.

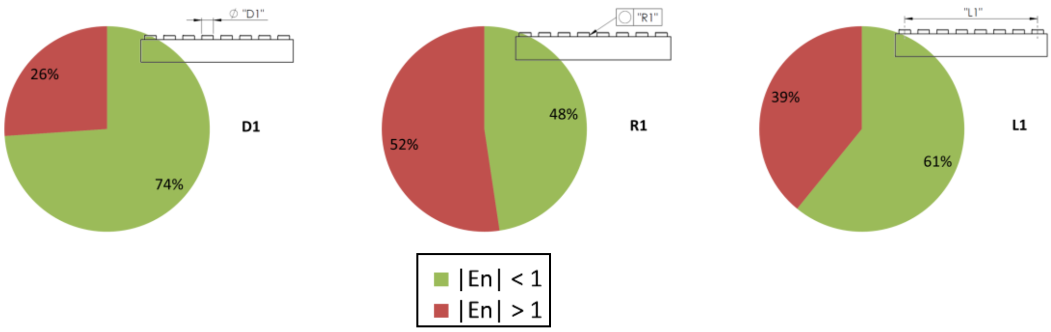


Figure 16: Distribution of E_n values for measurement of D1, R1 and L1 on Item 1.

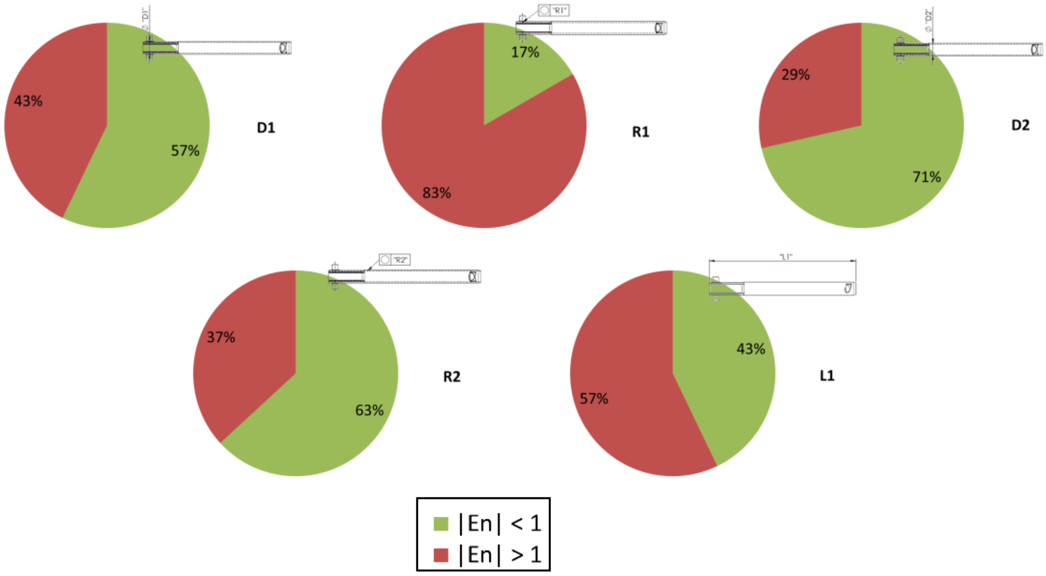


Figure 17: Distribution of E_n values for measurement of D1, R1, D2, R2 and L1 on Item 2.

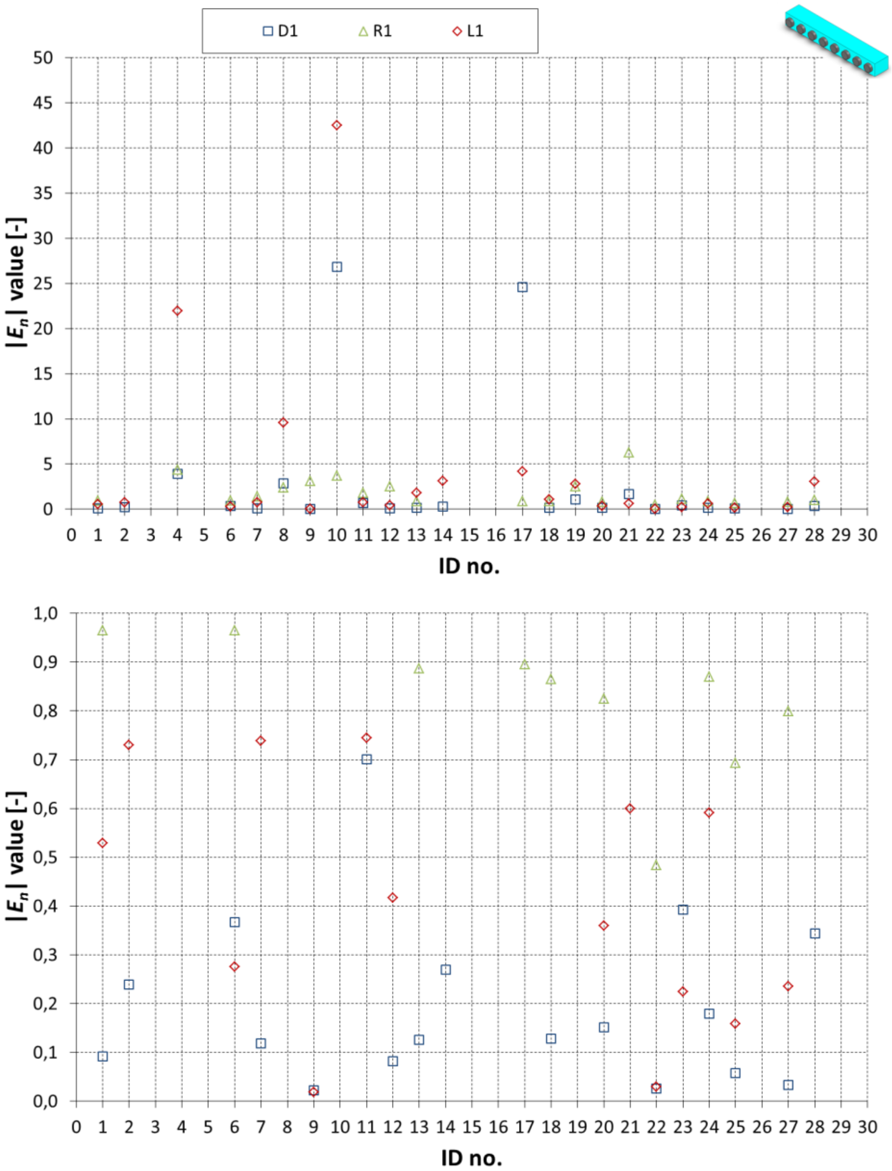


Figure 18: E_n results for Item 1 for all measurands. Top: range up to |E_n| = 50. Bottom: range up to |E_n| = 1.0.

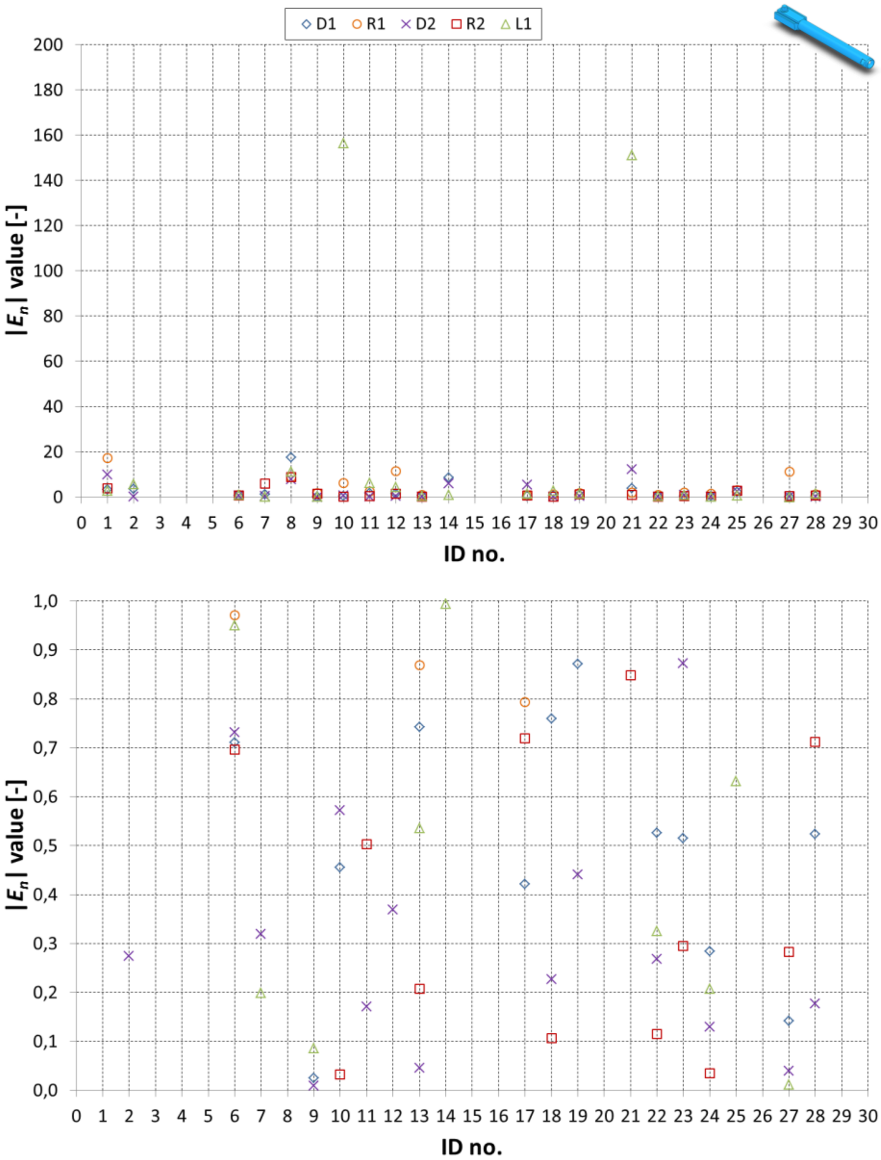


Figure 19: E_n results for Item 2 for all measurands. Top: range up to $|E_n|$ = 200. Bottom: range up to $|E_n|$ = 1.0.

A histogram showing the distribution of all E_n values calculated for Item 1 and Item 2 is shown in Figure 20 and the distribution in percentage is shown in Table 15 . About 55 % of the main results are in agreement with the reference values.

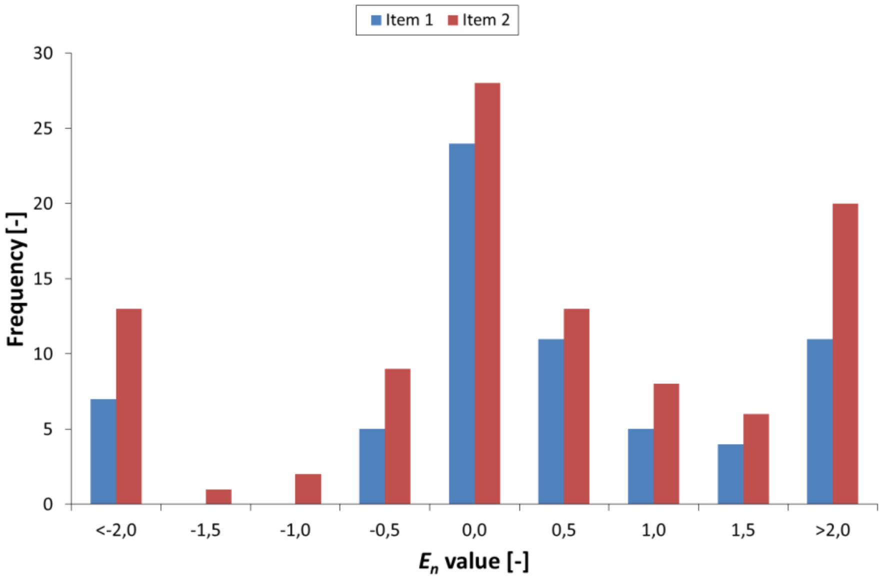


Figure 20: Histogram for the distribution of all E_n values acquired for Item 1 and Item 2.

Table 15: Overview of the distribution of E_n values in percentage.

Type of measurement results	Number of measurement results	Percentage [%]
|En| < 1	92	55
|En| > 1	75	45
TOTAL	167	100

An estimation of new uncertainties leading to $|E_n|$ = 0.99 was carried out for the results with $|E_n|$ values larger than 1, see Table 16. Some results were identified as outliers using the interquartile rule for outliers [Johnson, 2005], and excluded from calculations. Outliers are marked with italic in Table 16. It was concluded that likely uncertainties for the laboratories considered in Table 16 would lie in the range 14-53 µm. This approach is limited by the fact that all deviations are treated as random, including systematic errors, yet it clearly indicates that uncertainties of 8-12 µm stated by the participants are underestimated.

Table 16: Estimation of new uncertainties leading to |E_n| = 0.99 for the results with |E_n| values larger than 1. Values in mm. Identified outliers are shown in italic. AVG, MAX and MIN are calculated excluding outliers.

	Item 1			Item 2				
ID no.	*D1*	*R1*	*L1*	*D1*	*R1*	*D2*	*R2*	*L1*
1				0.0299	0.1576	*0.0902*	0.0353	0.0295
2				0.0188				0.0322
3								
4	0.0082	0.0111	0.1266					
5								
6								
7		0.0127		0.0117			0.0532	
8	0.0107	0.0250	0.1185	0.0419	0.0478	0.0206	0.0455	0.0707
9		0.0160	0.0132		0.0104		0.0066	0.0536
10	0.0694	*0.0343*	*0.7675*		0.0688			*0.5945*
11		0.0060		0.0047	0.0069			0.0294
12		0.0128		0.0147	0.0549		0.0074	0.0461
13			0.0234					
14			0.0192	0.0300		0.0187		
15								
16								
17	*0.2824*		0.0450			0.0369		0.0310
18			0.0190		0.0075			0.0306
19	0.0006	0.0188	0.0157		0.0135		0.0088	0.0065
20								
21	0.0097	0.0151		0.0269	0.0977	0.0493		*0.6150*
22					0.1092			
23		0.0092			0.0170			0.0083
24					0.0147			
25				0.0217	0.0306	0.0241	0.0248	
26								
27					0.1330			
28		0.0091	0.0637		0.0236			0.0442
AVG	0.0197	0.0136	0.0494	0.0223	0.0529	0.0299	0.0259	0.0347
MAX	0.0694	0.0250	0.1266	0.0419	0.1576	0.0493	0.0532	0.0707
MIN	0.0006	0.0060	0.0132	0.0047	0.0069	0.0187	0.0066	0.0065

3.5. Involved industrial CT scanners by the participants

The frequency of instrument types is shown in Figure 21. The frequency of MPE values is shown in Figure 22. 9 out of 27 participants had a sensor of the type Perkin Elmer and 23 out of 27 participants used an area sensor, see Figure 23 and Figure 24. Deviation from reference values vs. detector pixel size are shown in Figure 25. Deviation from reference values vs. maximum resolution are shown in Figure 26 for Item 1 and Figure 27 for Item 2.

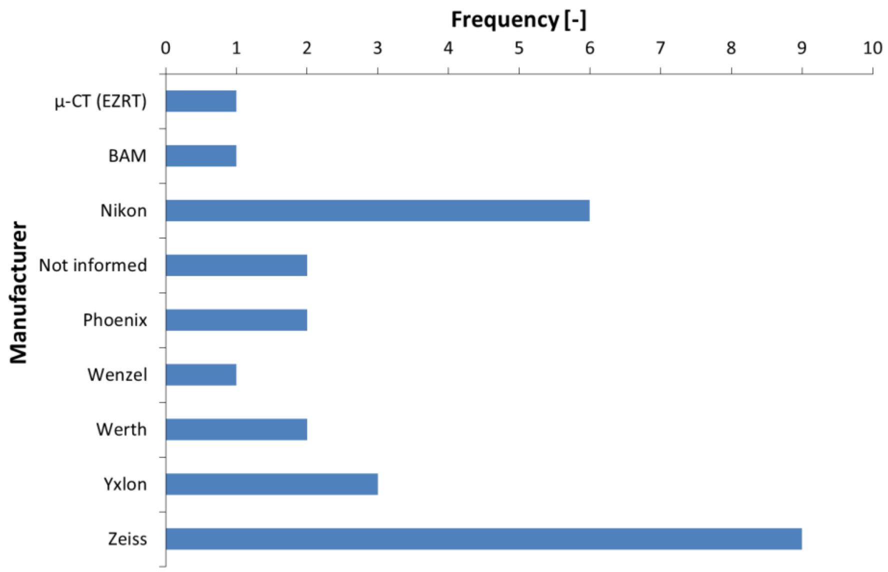


Figure 21: Frequency of instrument types.

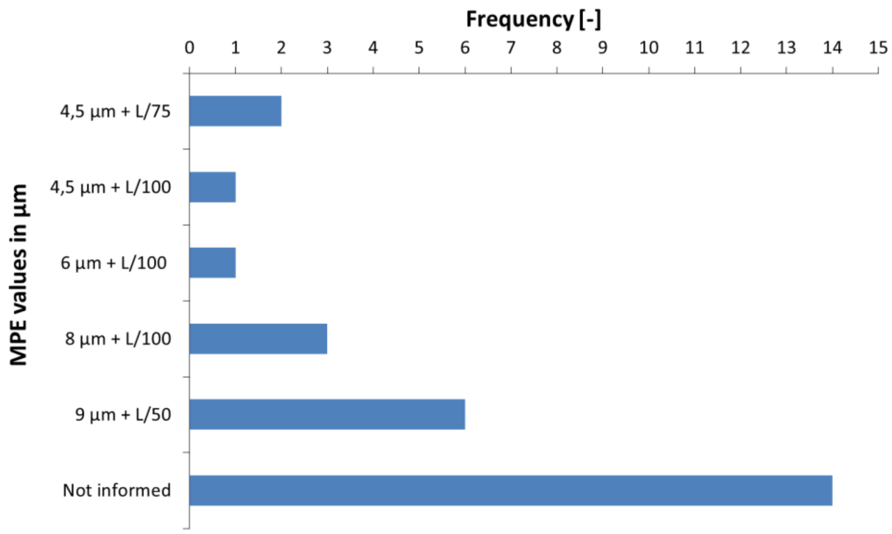


Figure 22: Frequency of MPE values.

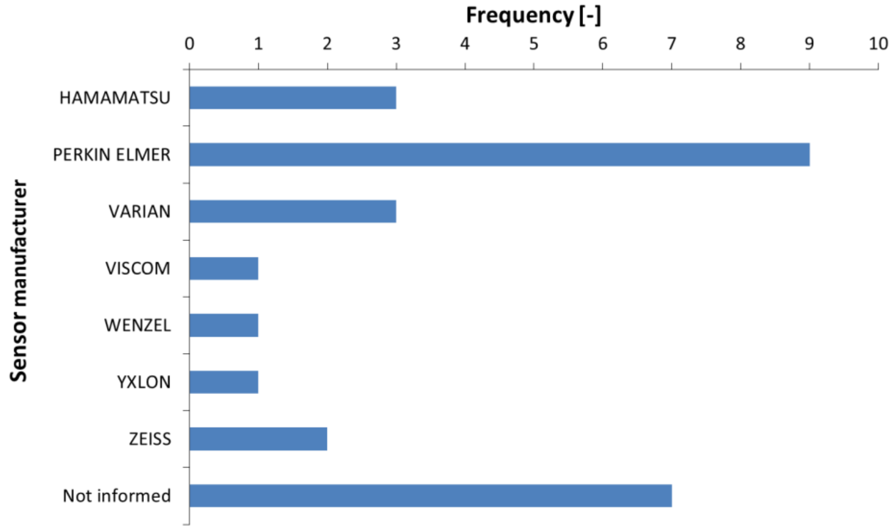


Figure 23: Frequency of sensor manufacturer.

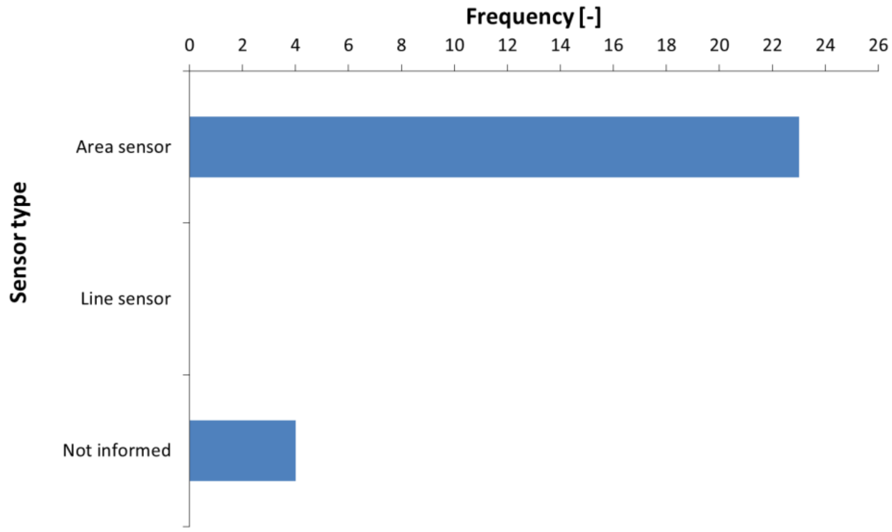


Figure 24: Frequency of sensor type.

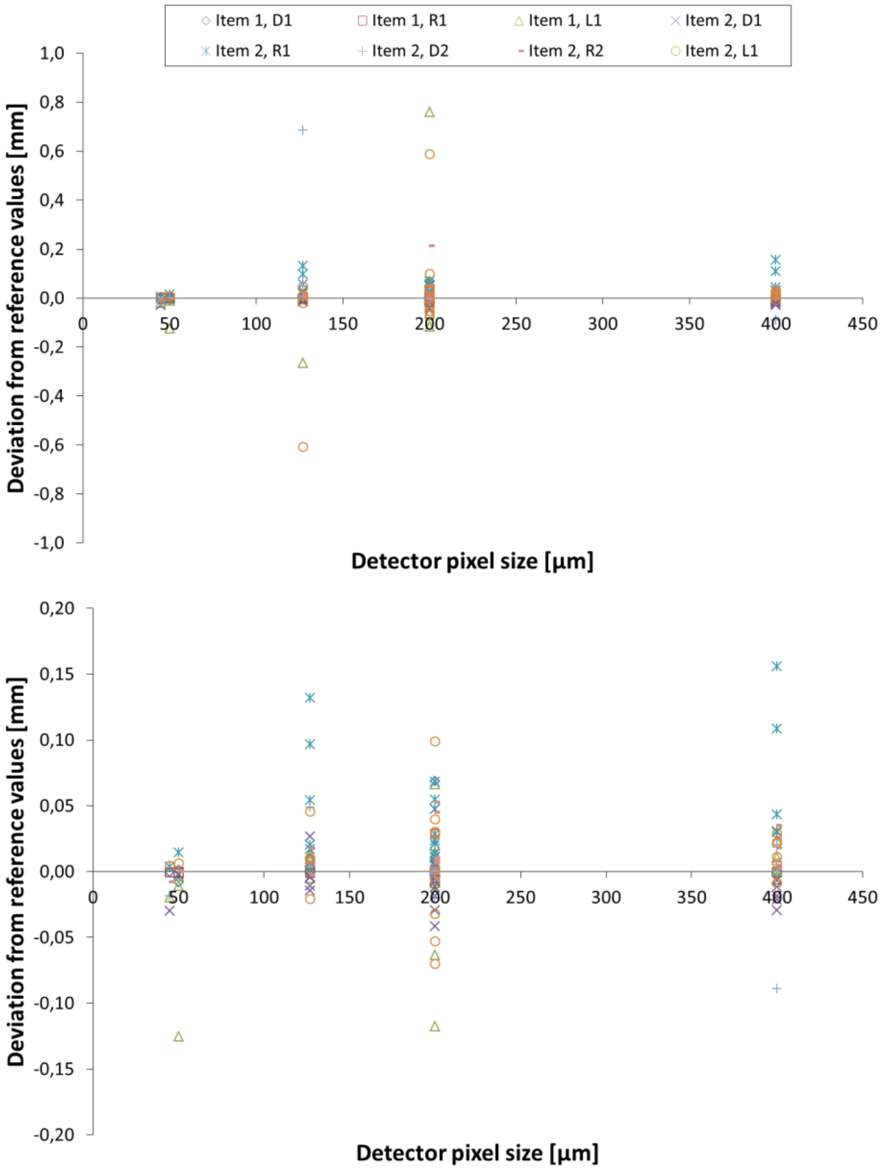


Figure 25: Deviation from reference values vs. detector pixel size. Top: range ± 1 mm. Bottom: range ± 0.2 mm.

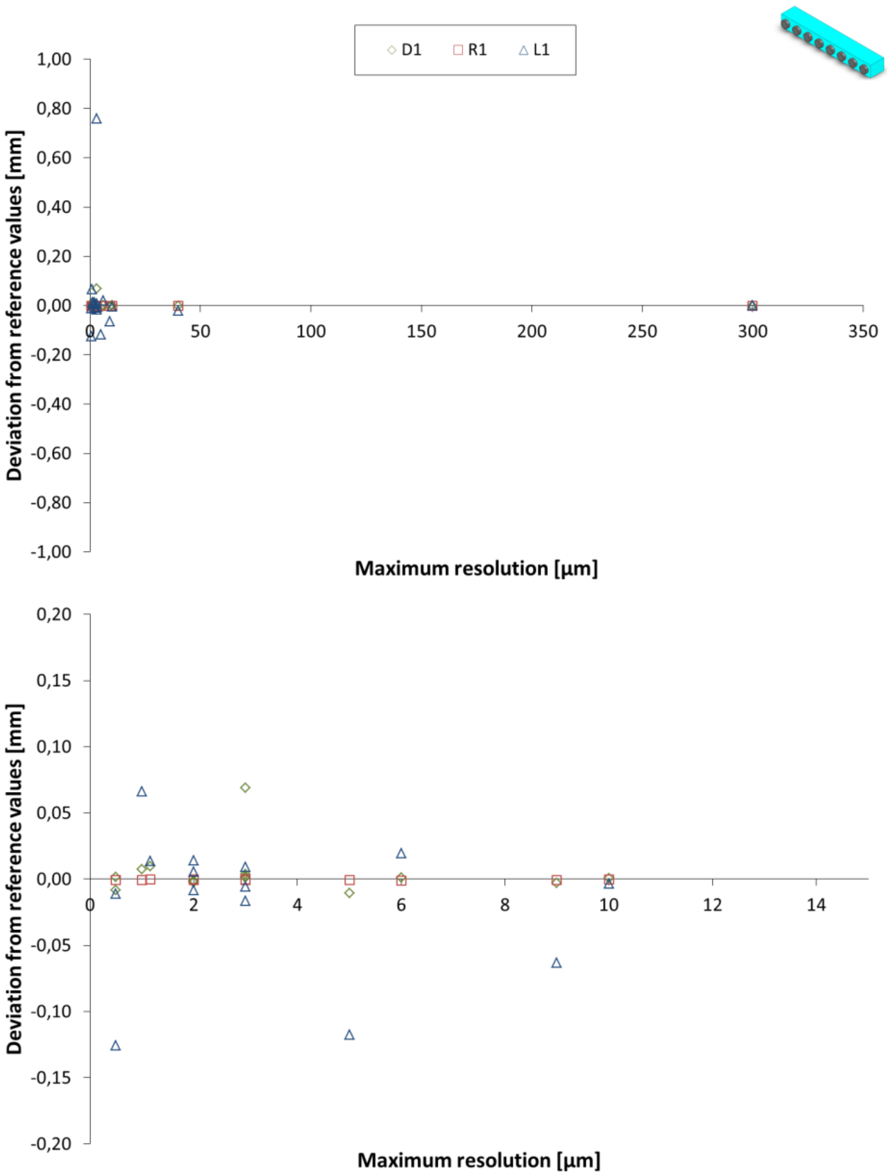


Figure 26: Deviation from reference values vs. maximum resolution for Item 1. Top: range ± 1.0 mm with resolution range 0 to 350 µm. Bottom: range ± 0.2 mm with resolution range 0 to 14 µm.

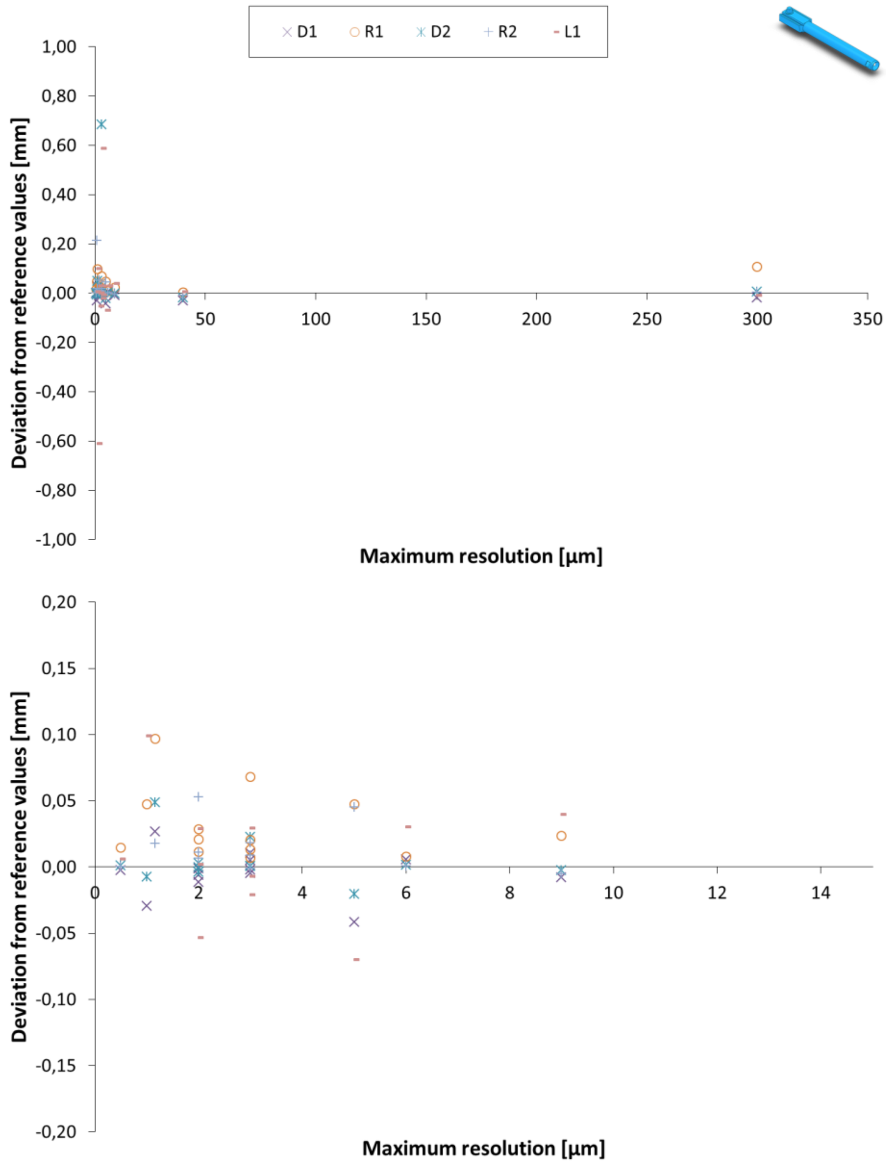


Figure 27: Deviation from reference values vs. maximum resolution for Item 2. Top: range ± 1.0 mm with resolution range 0 to 350 µm. Bottom: range ± 0.2 mm with resolution range 0 to 14 µm.

3.6. Applied software by the participants

8 out of 27 participants had acquisition software of the type Zeiss Metrotom OS, see Figure 28. 8 out of 27 participants had reconstruction software of the type Zeiss Metrotom OS, see Figure 29. 11 out of 27 participants had analysis software of the type VGStudioMAX, see Figure 30.

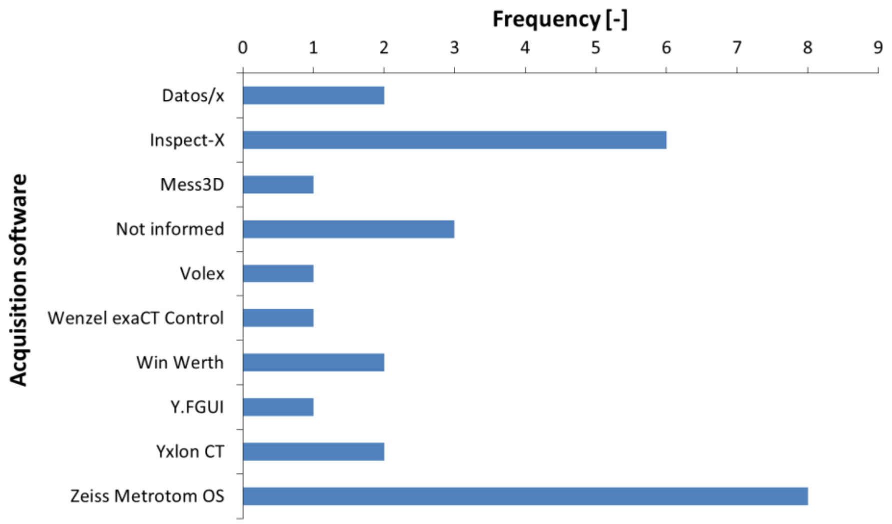


Figure 28: Frequency of acquisition software.

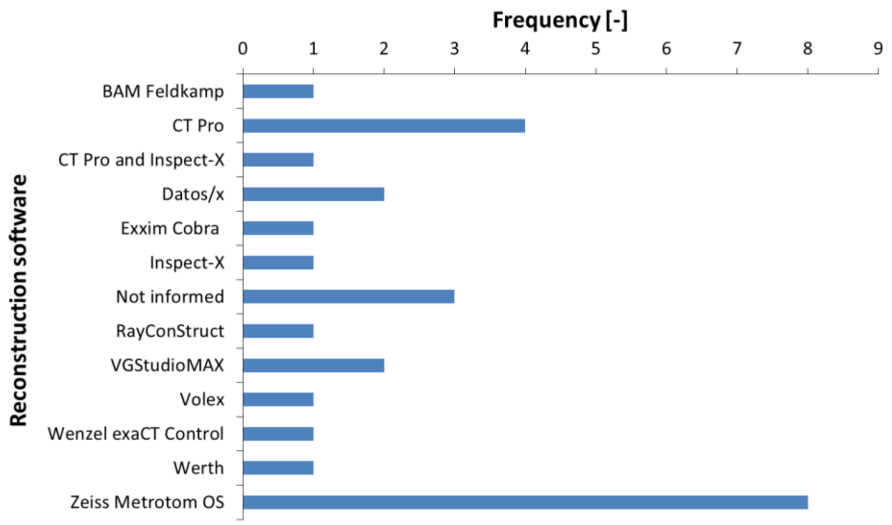


Figure 29: Frequency of reconstruction software.

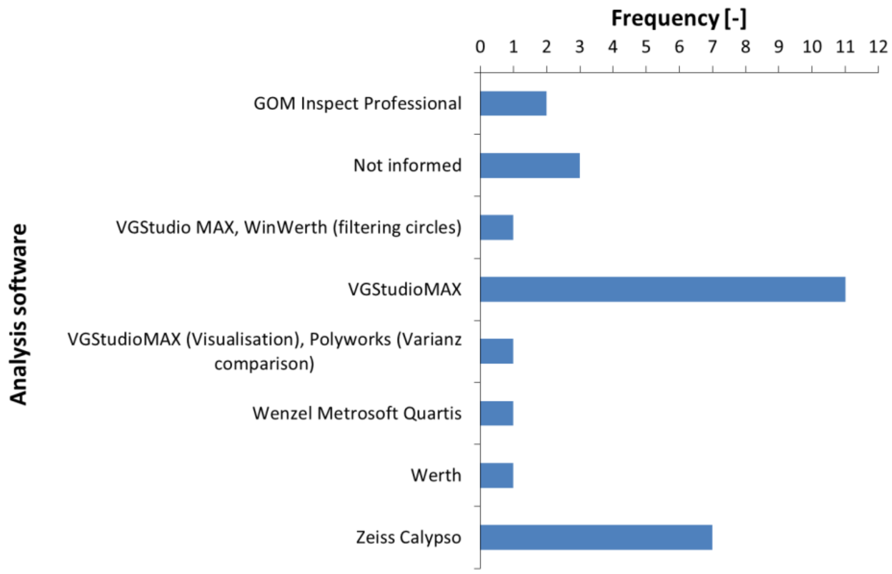


Figure 30: Frequency of analysis software.

3.7. Impact of instrument settings and operator

18 out of 27 participants had orientated Item 1 in an inclined way (see Figure 31), which is known to minimize beam hardening artefacts and blurred edges. For Item 2, 16 out of 27 participants had orientated the item in an inclined way. 13 out of 27 participants did not apply a filter for Item 1, see Figure 32. For Item 2, 5 out of 27 participants applied a Cu filter with a thickness on 1 mm, see Figure 33. 17 out of 27 participants did not apply a selected region of interest (ROI) for Item 1, see Figure 34. For Item 2, 16 out of 27 participants did not apply ROI. 6 out of 27 participants had scanned Item 1 in a temperature controlled room with good thermal conditions (T = 20 °C). The number of Item 2 was analogical to the one for Item 1, see Figure 35. 12 out of 27 participants had scanned Item 1 one time, when 11 out of 27 participants had scanned Item 2 once, see Figure 36. The frequency of scale error correction is shown in Figure 37, where 7 out of 27 participants had performed a scale error correction. Current versus voltage is shown in Figure 38, where it can be seen that a higher voltage was used for Item 2 compared to Item 1. This is related to the needed voltage to penetrate Item 2, because of the higher material density. The current seems similar for both items. The power is of interest, because it indicates the costs related to electricity use. The power *P* is calculated based on data for current *I* and voltage *U*, see Equation 4.

$$P = U \cdot I \tag{4}$$

The frequency of the power is shown in Figure 39 for Item 1 and Item 2. It can be seen that the needed power is a little higher for Item 2 compared to Item 1, which may be due to the increased voltage to penetrate Item 2. Deviation from reference values vs. focus spot size is shown in Figure 40 for Item 1 and Figure 41 for Item 2. The data for the geometrical magnification *m*, source-detector distance *SDD*, source-object distance *SOD*, and detector pixel size *p* are not shown in this report, but these factors are involved in the calculations for the voxel size *s*, see Equation 5.

$$s = \frac{p}{m} = p \cdot \left(\frac{SOD}{SDD}\right) \tag{5}$$

Deviations from reference values vs. voxel size are shown in Figure 42 for Item 1 and Figure 43 for Item 2. Applied voxel sizes *s* by the participants is reported in Table 17 and calculated based on detector pixel size *p*, source-detector distance *SDD* and source-object distance *SOD*. Deviation from reference values vs. number of projections is shown in Figure 44 for Item 1 and Figure 45 for Item 2. Frequency of integration time is shown in Figure 46. Frequency of no. of image averaging is shown in Figure 47. Frequency of binning is shown in Figure 48. Binning can be used to reduce quantity of data by merging groups of pixels in virtual pixels. Frequency of scanning time is shown in Figure 49. Frequency of artefacts for scale error correction is shown in Figure 50. Frequency of surface determination method is shown in Figure 51. Frequency of data filtering is shown in Figure 52. Frequency of voxel (volume) and STL (surface) data is shown in Figure 53. Frequency of fixture material is shown in Figure 54.

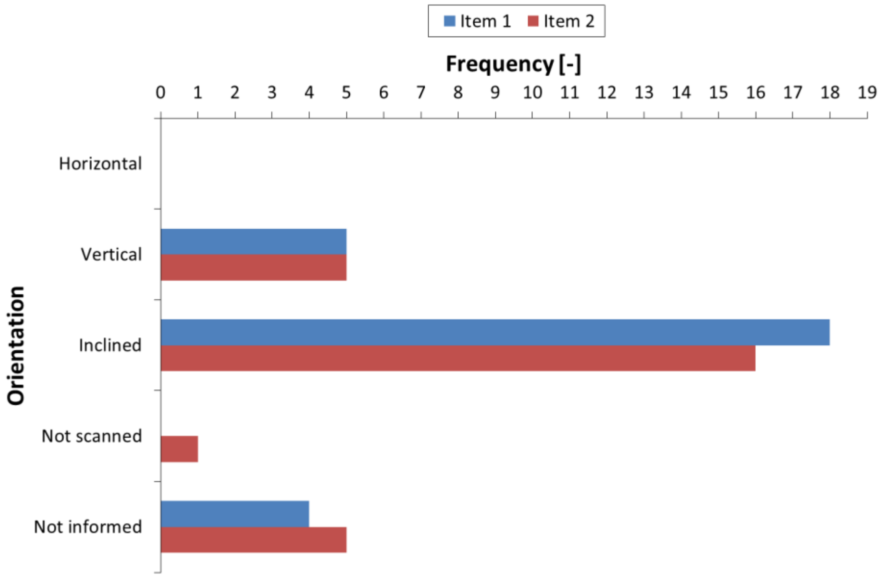


Figure 31: Frequency of orientation of scanned items.

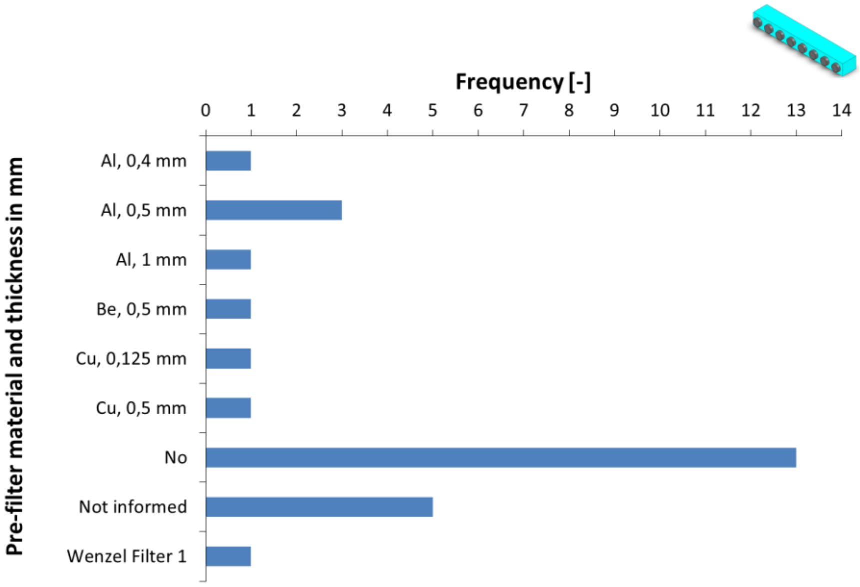


Figure 32: Frequency of pre-filter material and thickness in mm for Item 1.

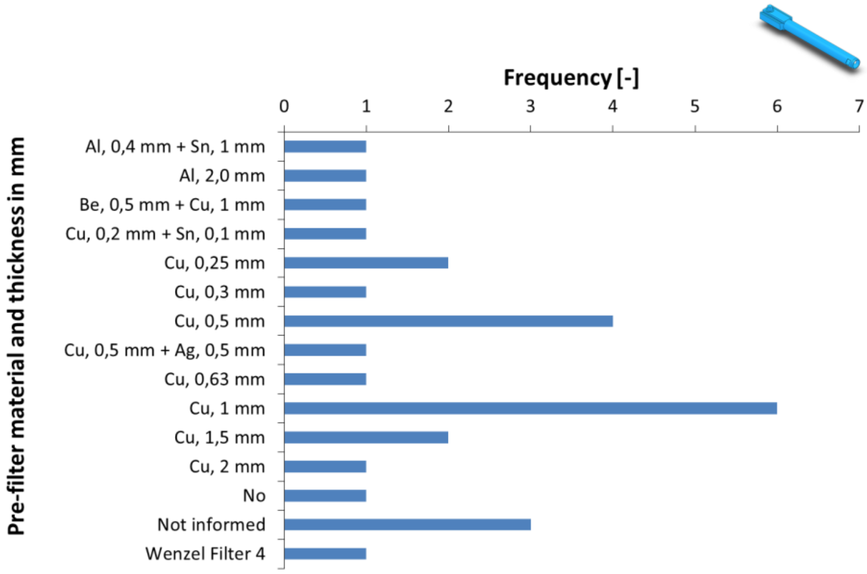


Figure 33: Frequency of pre-filter material and thickness in mm for Item 2.

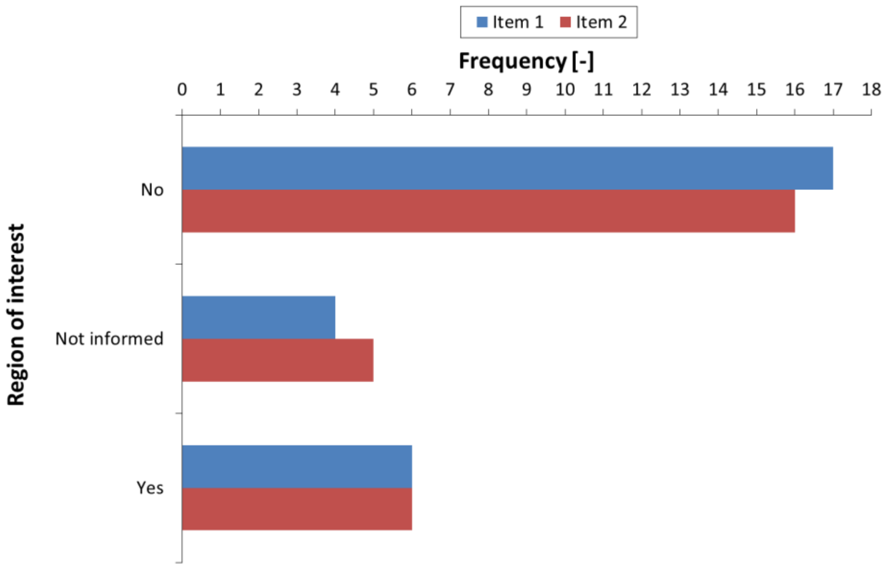


Figure 34: Frequency of ROI.

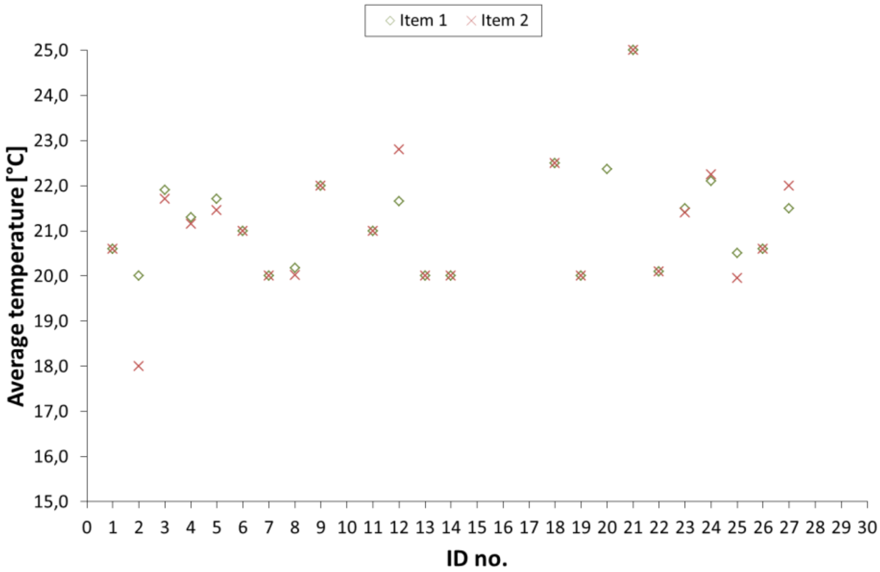


Figure 35: Temperature inside the CT scanner.

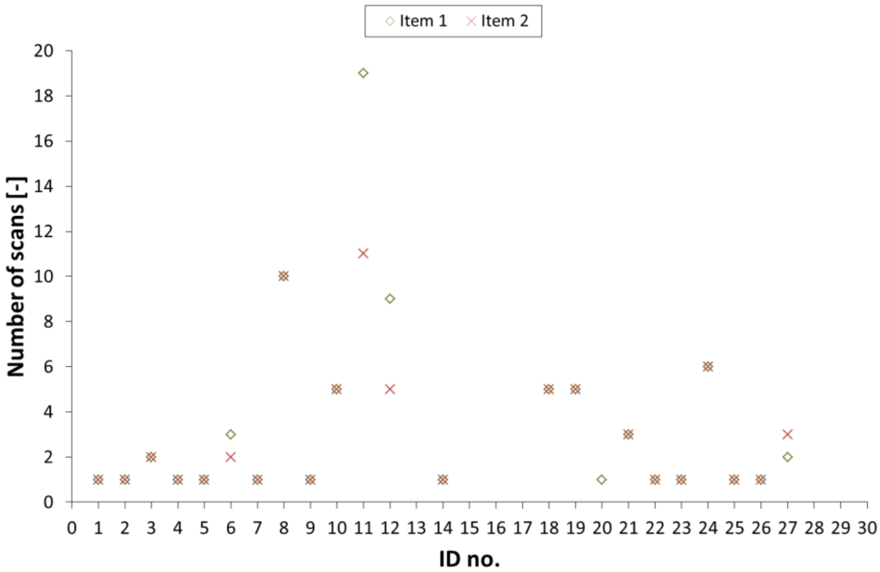


Figure 36: Number of scans by participants.

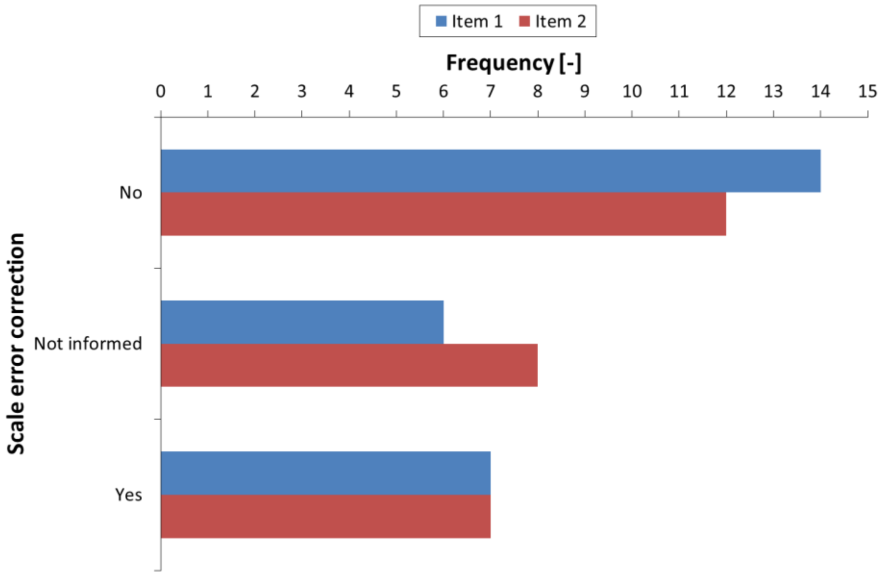


Figure 37: Frequency of scale error correction.

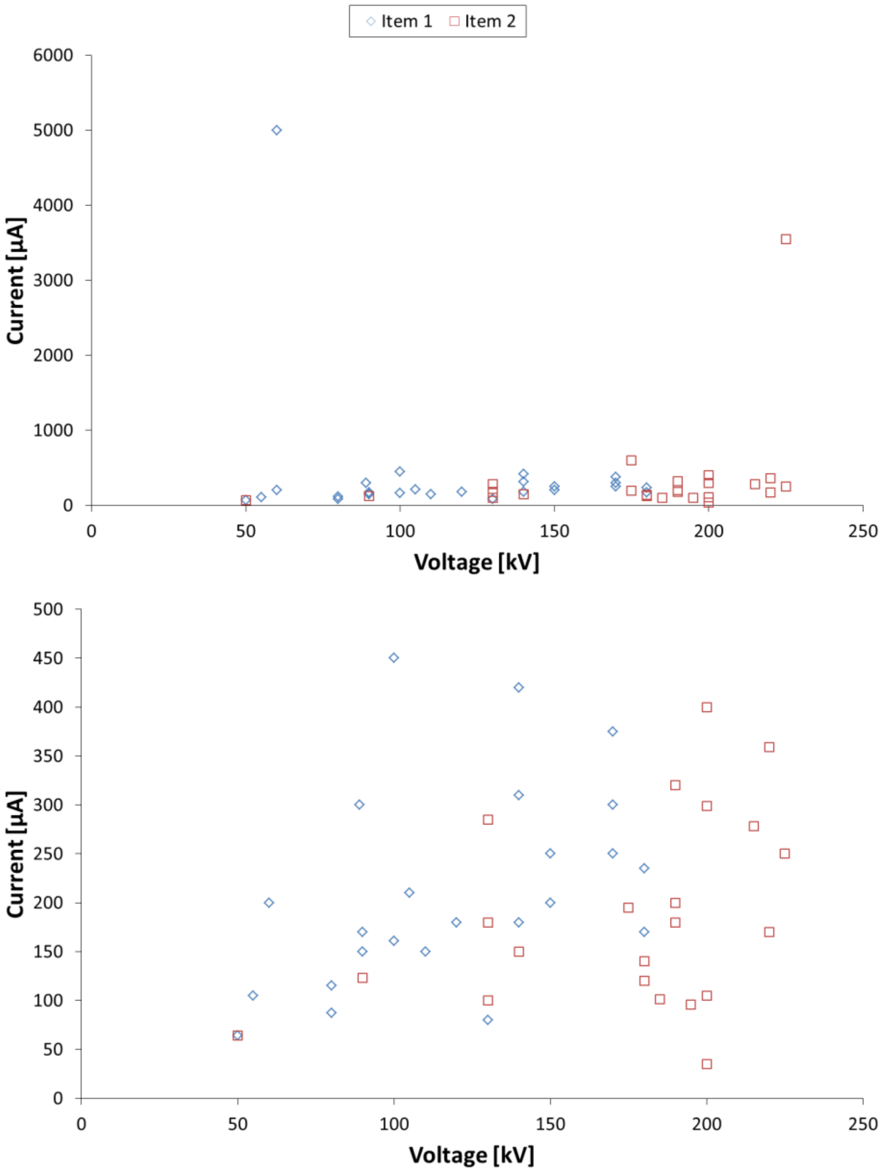


Figure 38: Current vs. voltage. Top: range 0 to 6000 µA. Bottom: range 0 to 500 µA.

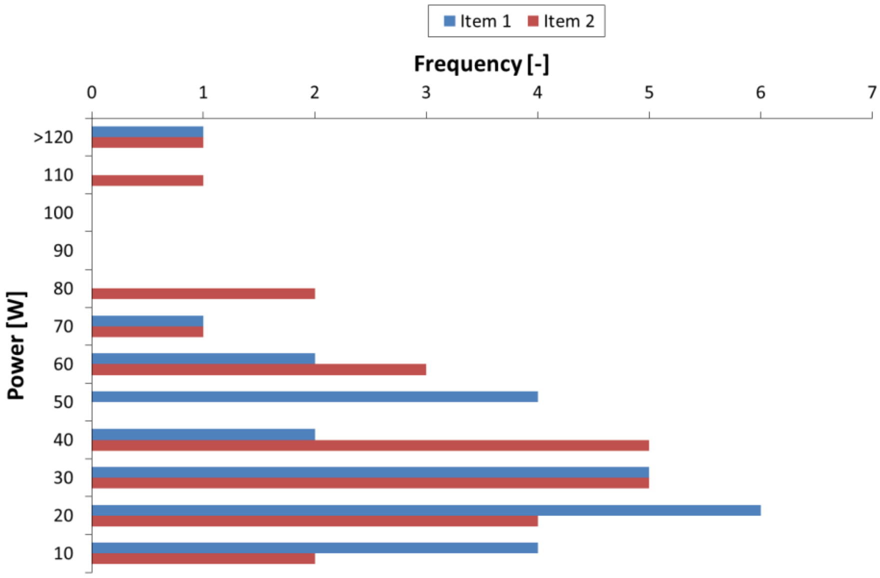
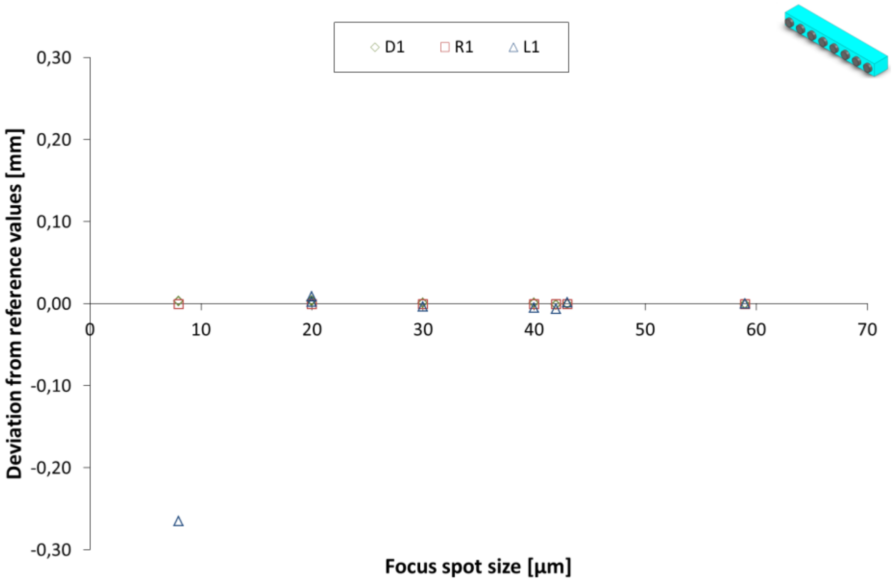


Figure 39: Frequency of power of scanned items.



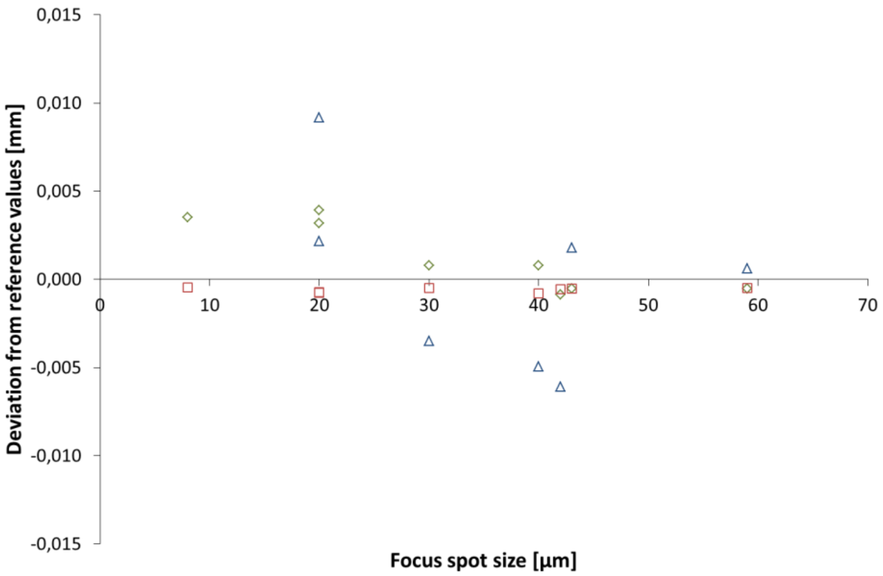


Figure 40: Deviation from reference values vs. focus spot size for Item 1. Top: range ± 0.3 mm. Bottom: range ± 0.015 mm.

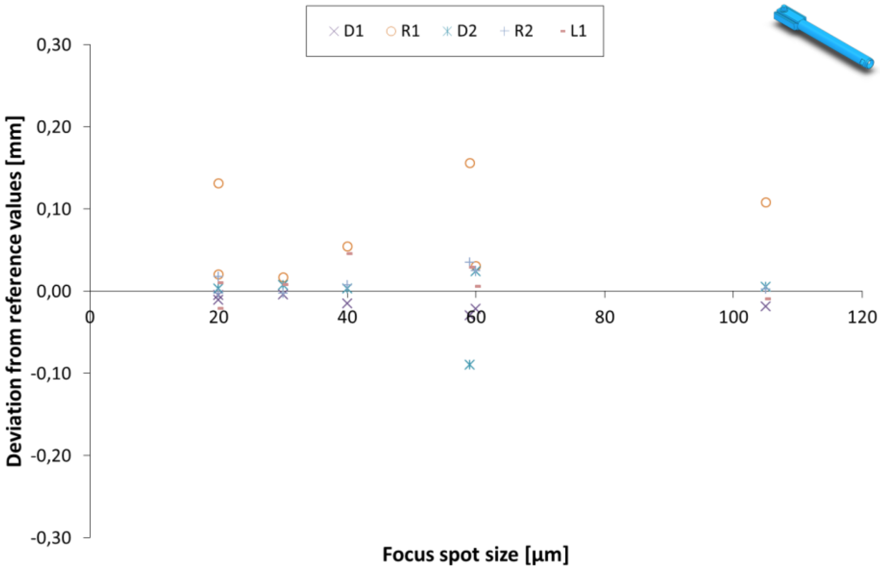
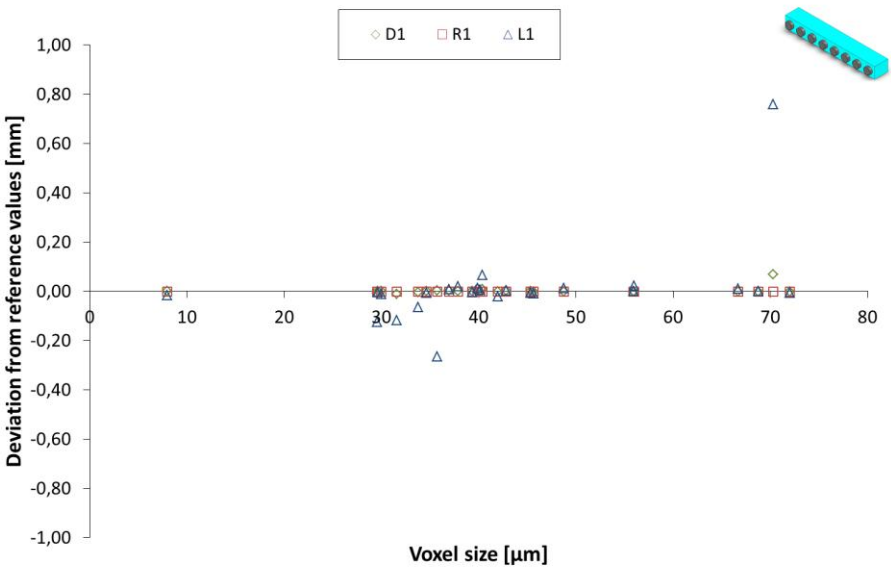


Figure 41: Deviation from reference values vs. focus spot size for Item 2.



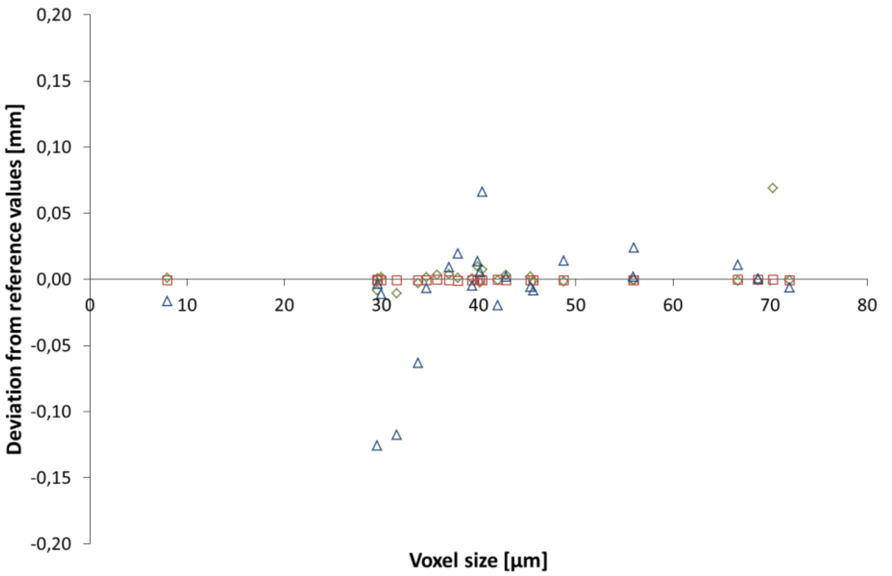


Figure 42: Deviation from reference values vs. voxel size for Item 1. Top: range ± 1.0 mm. Bottom: range ± 0.2 mm.

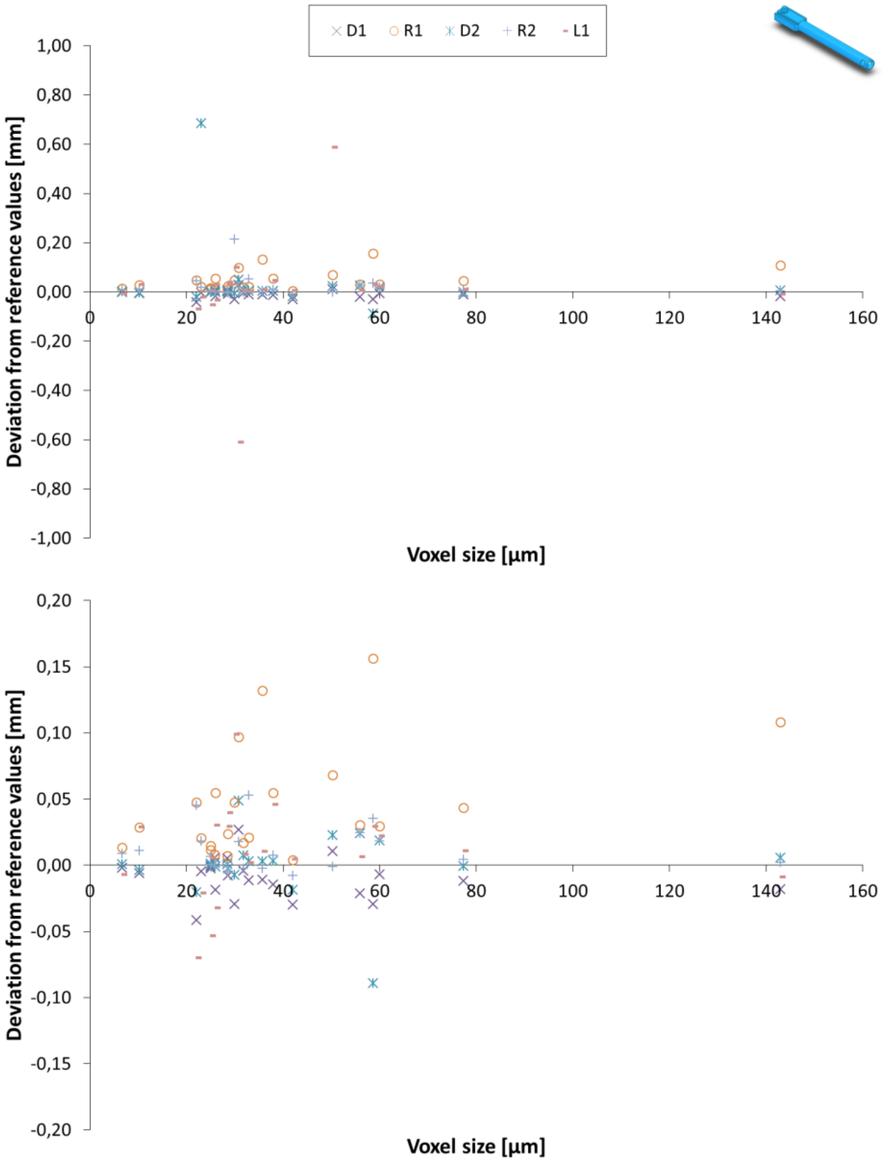


Figure 43: Deviation from reference values vs. voxel size for Item 2. Top: range ± 1.0 mm. Bottom: range ± 0.2 mm.

Table 17: Voxel sizes used by the participants.

ID no.	Voxel size for Item 1 [μm]	Voxel size for Item 2 [μm]
1	72.0	58.7
2	34.6	26.0
3	40.4	29.9
4	29.6	22.4
5	37.0	23.0
6	40.1	10.2
7	45.7	32.9
8	31.6	22.1
9	48.8	25.0
10	70.3	50.2
11	45.3	28.5
12	39.4	37.9
13	56.0	77.3
14	42.0	42.0
15		
16		
17		
18	37.9	25.9
19	8.0	6.7
20	29.6	N/A
21	39.9	30.8
22	68.8	143.0
23	42.9	31.8
24	30.0	25.0
25	55.9	55.9
26	66.7	60.0
27	35.7	35.7
28	33.8	28.6

AVG	43.3	38.7
MAX	72.0	143.0
MIN	7.9	6.7

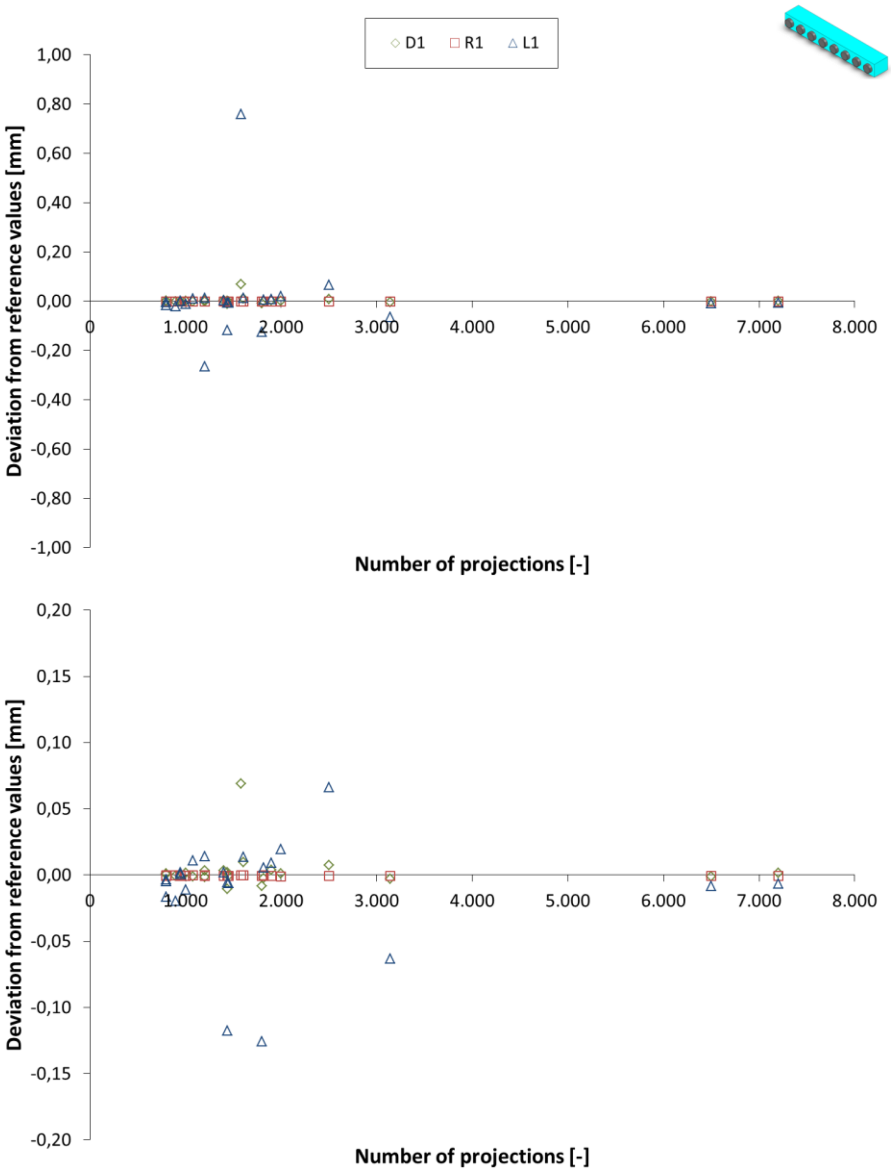
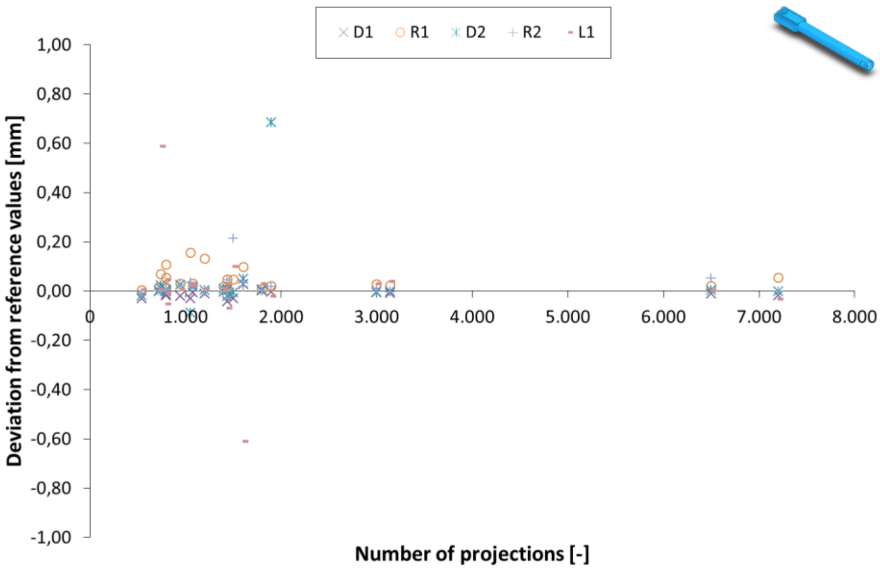


Figure 44: Deviation from reference values vs. number of projections for Item 1. Top: range ± 1.0 mm. Bottom: range ± 0.2 mm.



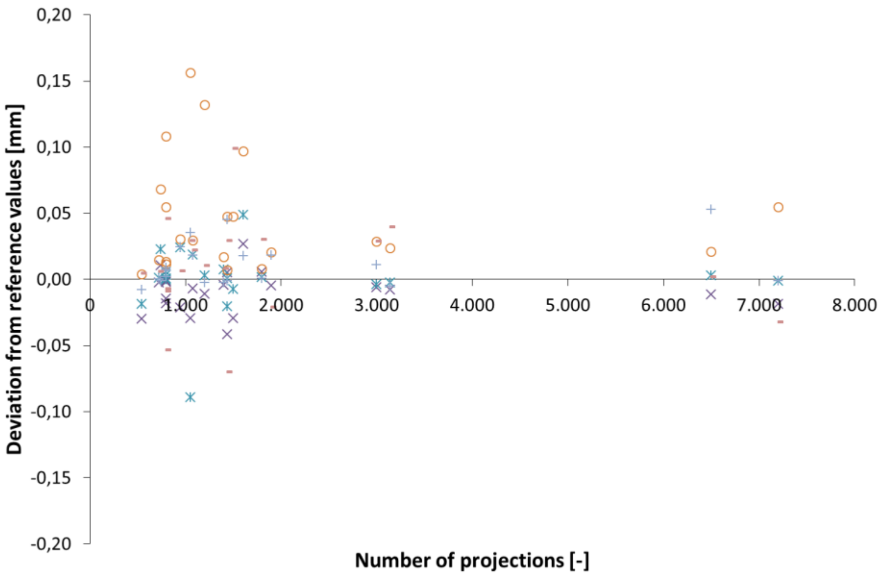


Figure 45: Deviation from reference values vs. number of projections for Item 2. Top: range ± 1.0 mm. Bottom: range ± 0.2 mm.

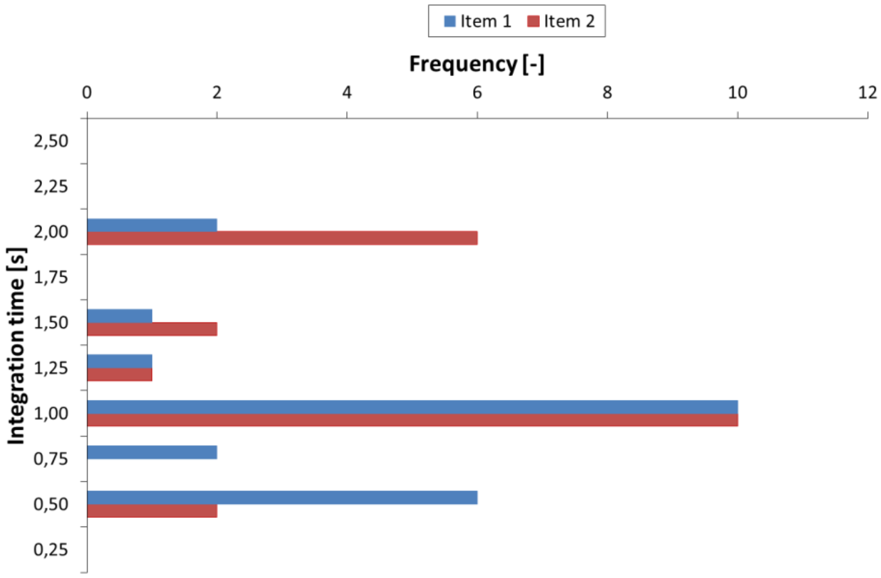


Figure 46: Frequency of integration time.

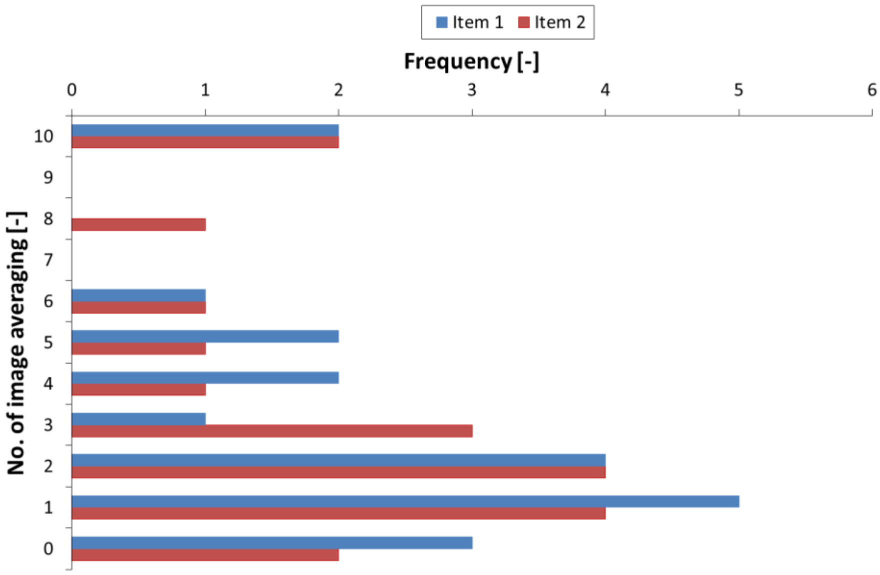


Figure 47: Frequency of no. of image averaging.

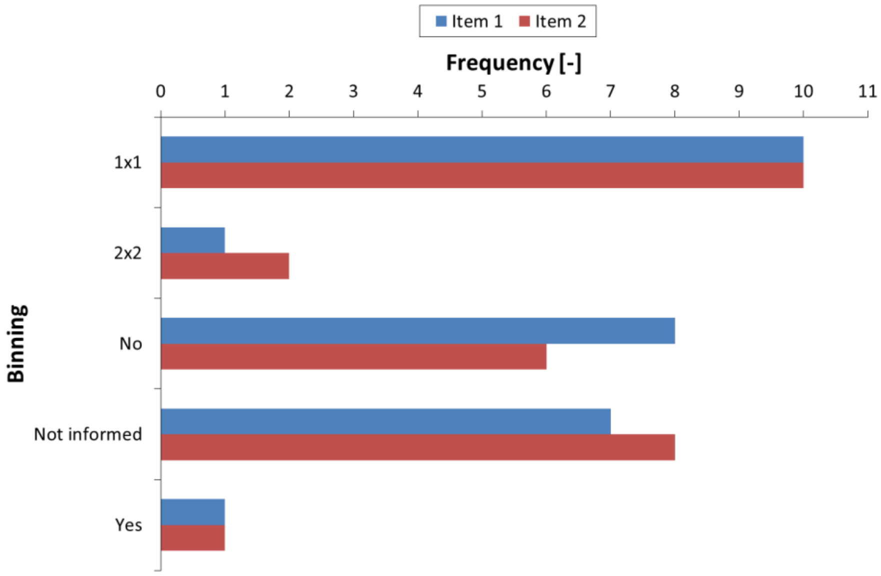


Figure 48: Frequency of binning.

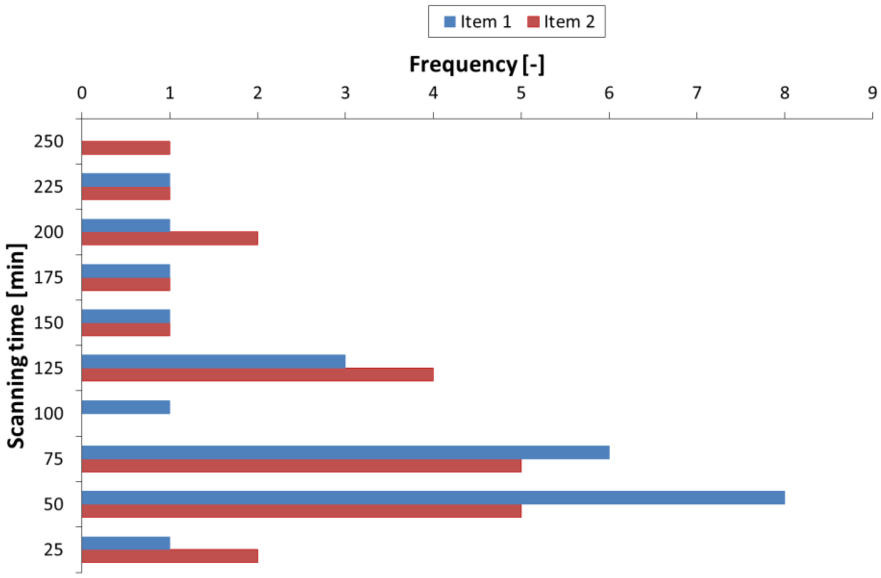


Figure 49: Frequency of scanning time.

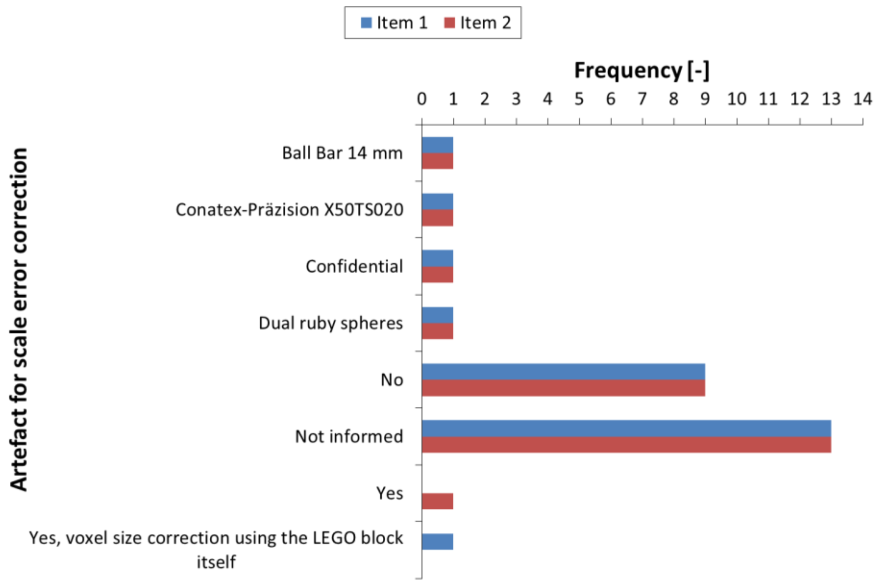


Figure 50: Frequency of artefacts for scale error correction.

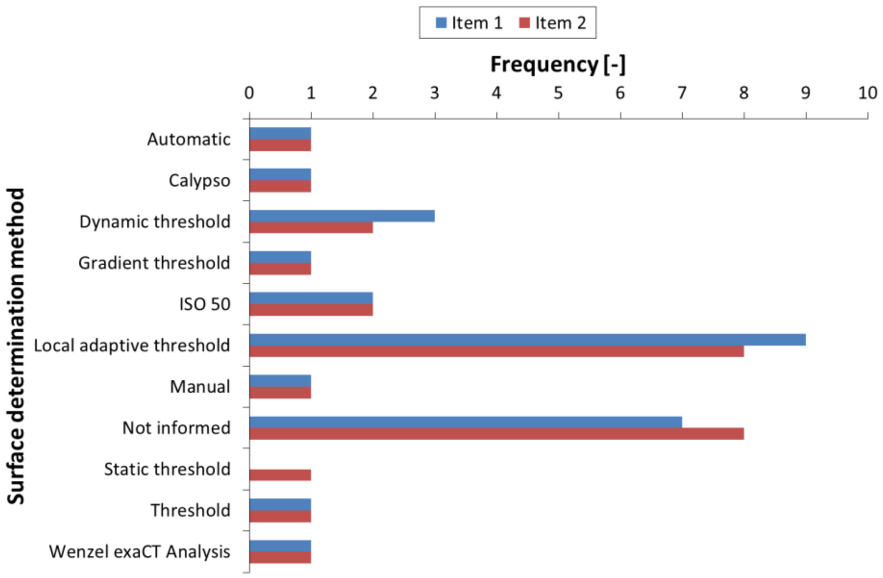


Figure 51: Frequency of surface determination method.

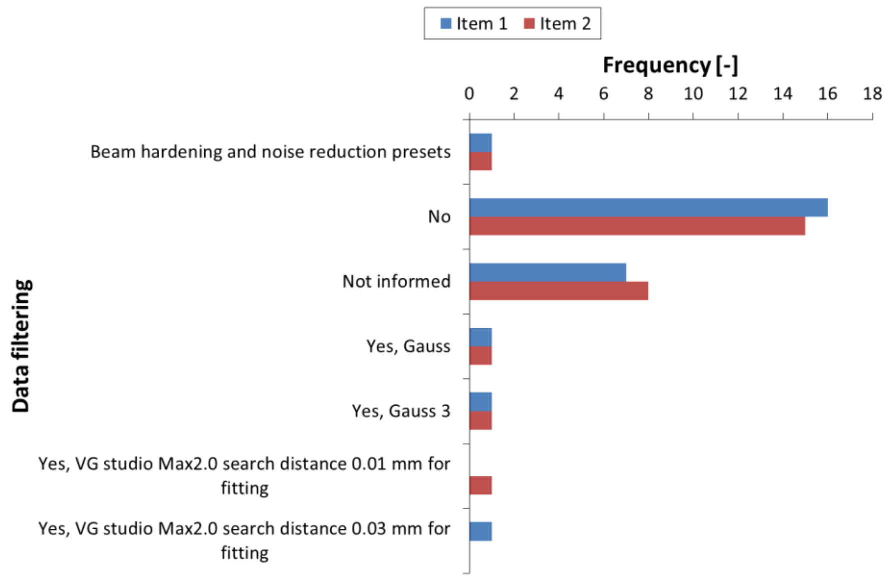


Figure 52: Frequency of data filtering.

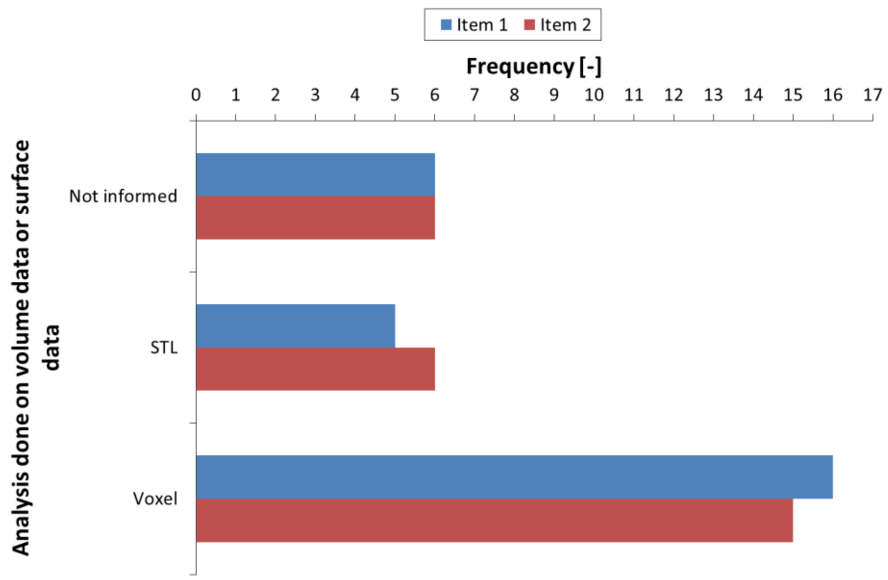


Figure 53: Frequency of voxel (volume) and STL (surface) data.

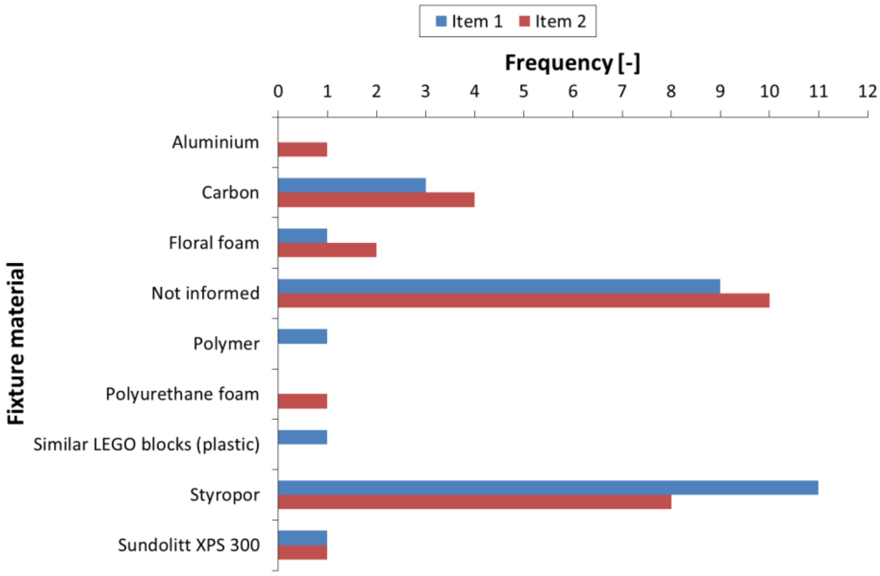


Figure 54: Frequency of fixture material.

3.8. Applied uncertainties by the participants

The frequency of uncertainties applied by the participants is shown in Figure 55. The frequency of uncertainty sizes is shown in Figure 56 for Item 1 and in Figure 57 for Item 2.

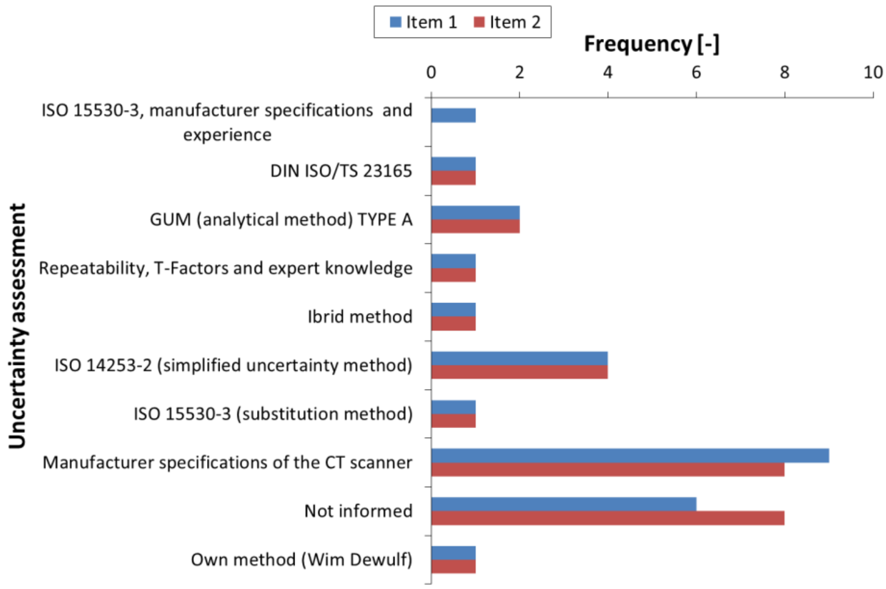


Figure 55: Frequency of applied uncertainties by the participants.

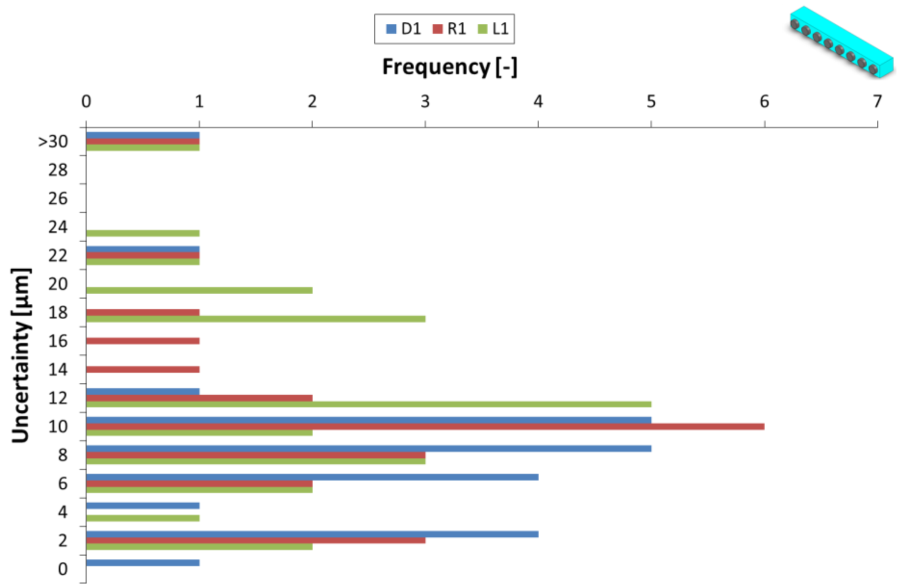


Figure 56: Frequency of uncertainty sizes for Item 1.

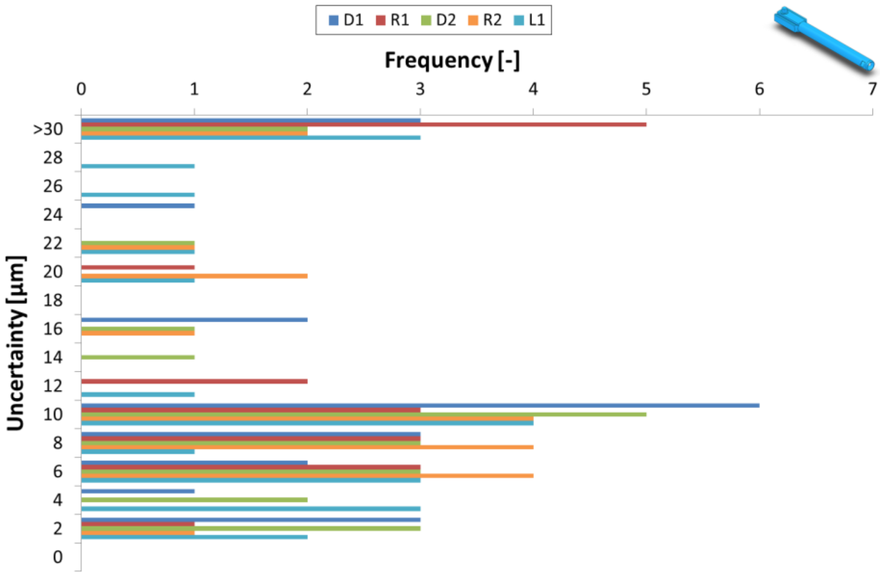


Figure 57: Frequency of uncertainty sizes for Item 2.

3.9. Further information from the participants

The measuring procedures were followed by all participants without problems.

Two participants have indicated that they have used subsidiary measuring instruments, such as, e.g., a CMM, but did not report those results or modify the CT results. The participants that have used subsidiary measuring instruments have the following IDs: 7 and 12.

4. Conclusion

The main conclusions which were drawn from the project are summarized in the following.

- Circulation started in January 2013, and was completed in July 2013. 27 participants from 8 countries participated.
- Thanks to excellent support by all participants, the circulation was smooth and timely, except for three participants who were delayed due to scanner problems.
- All together, 30 plastic items and 29 metal items were manufactured from industrial production and measured at CGM. 27 sets were circulated in parallel, one set per participant.
- Different measurands were considered, encompassing diameters, roundness, and lengths.
- Reference values for all 30 plastic- and 29 metal items were provided by CGM using coordinate measuring machines.
- Expanded measurement uncertainties obtained by CGM are in the range of 1.6-5.5 µm for the plastic part and 1.5-2.5 µm for the metal item.
- Stability of items was documented through comparison of measurements before and after the circulation.
- Both items have shown a good stability through the approx. 6 months circulation.
- The measuring procedures were followed by all participants without problems.
- Several industrial CT scanners were involved.
- Results by the single participants were compared with the reference values provided by CGM.
- Each participant can use the comparison results in this report to investigate the presence of systematic errors and/or any underestimation of uncertainties.
- The expanded uncertainties stated by the participants are in the range 8-12 µm for both items and all measurands.
- Out of a total of 167 results obtained by the participants using CT scanning, 55% of the measurements yield $|E_n|$ values less than 1 and 45% larger than 1.
- More realistic uncertainties were estimated for the cases where $|E_n| \geq 1$, and values in the range 14-53 µm were suggested.
- In the measurements of diameters and roundness for both plastic- and metal items, the applied filters have no major effect on the results.
- For the diameters and lengths for both items, there is a good agreement between most participants' results and the reference values, except for few participants, which could be due to measurement errors as threshold determination, non-corrected scale and/or temperature corrections.
- The roundness for both items measured by the participants is higher than the unfiltered reference value. It is clear that form measurements are more problematic compared to size measurements because form measurements are more affected by the influence of scatter and noise of CT data.
- A clear influence from the surrounding wall thickness on the measurement of roundness was documented for the metal item.
- 18 out of 27 participants had orientated the plastic item in an inclined way, which is known to minimize beam hardening artefacts and blurred edges. For the metal item, 16 out of 27 participants had orientated the item in an inclined way.
- 13 out of 27 participants did not apply a filter for the plastic item. For the metal item, 5 out of 27 participants applied a copper filter with a thickness on 1 mm.

* 17 out of 27 participants did not apply a selected region of interest (ROI) for plastic item. For the metal item, 16 out of 27 participants did not apply ROI.
* 6 out of 27 participants had scanned the plastic item in a temperature controlled room with good thermal conditions (T = 20 °C). The number of metal item was analogous to the one for the plastic item.
* 12 out of 27 participants had scanned the plastic item one time, while 11 out of 27 participants had scanned the metal item once.
* 7 out of 27 participants had performed a scale error correction.
* A higher voltage was used for the metal item compared to the plastic item. This is related to the higher material density.
* The distribution for the current seems similar for both items.
* The needed power is a little higher for the metal item compared to the plastic item, which may be due to the increased voltage to penetrate the metal item.
* An applied voxel size by the participants was calculated based on detector pixel size, source-detector distance and source-object distance. The average voxel size for the plastic item was 43.3 µm, while it was 38.7 µm for the metal item.
* Statistics related to the used equipment and procedures show that participants, generally, have followed state of the art procedures for their measurements.
* The industrial items are suitable artefacts for CT measurements of this kind.
* After completion of the comparison, each participant has been offered to keep a set used for the measurements.

5. References

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6. Appendix

CIA-CT comparison
Measurement report for Item 1

GENERAL INFORMATION

Participant short name	
Participant number	
Contact person	
Operator	

CT SCANNER

Instrument type (manufacturer)	
Maximum resolution in µm	
MPE values in µm (if known)	
Detector type (manufacturer)	
Detector type (line detector, area detector)	
Detector pixel size in µm	

SOFTWARE

Acquisition software	
Reconstruction software	
Analysis software	

SETUP AND SCANNING

Orientation of the item (+ photo)	
Hard filter: Pre-filter material and thickness in mm (if applied)	
ROI (Y/N)	
Temperature inside scanner before and after scannning in °C	
Number of scans per item	
Artefact for scale error correction (if applied) (+ photo)	
Voltage in kV	
Current in µA	
Power in W	
Focus spot size in µm (if known)	
Source-detector distance in mm	
Source-object distance in mm	
Geometrical magnification	
Original voxel size in µm	
No. of views (projections)	
Integration time in s	
No. of image averaging	
Binning	
Scanning time in min	

PROCESSING PARAMETERS

Reconstruction: As each reconstruction software enables to apply different setting parameters, you can provide the parameters which you find the most relevant for us to know. This can be for example in case you apply any beam hardening correction, noise reduction, etc.	
Scale error correction (Y/N)	
Voxel size after scale correction in µm	
Surface determination method (threshold)	
Data filtering (Y/N and what type of filter)	
Analysis done on volume data (original voxel data) or surface data (STL)	

UNCERTAINTY ASSESSMENT	**LIST OF UNCERTAINTY CONTRIBUTORS**
Method (indicate what of the following is used)	1)
1) GUM (analytical method)	2)
2) ISO 14253-2 (simplified uncertainty method)	3)
3) ISO 15530-3 (substitution method)	…
4) VDI/VDE 2617-7 (simulation)	
5) Manufacturer specifications of the CT scanner	
6) Other	

ATTACHMENTS	**Name of attachment**
Photos of item and fixture on rotary table	
Description of fixture material and shape	
Raw CT data (e.g. .vgi)	
Processed CT data (e.g. .vgl)	
STL files (if relevant)	
Polar plots relative to *D1* and *R1*	
Photographs	
Other relevant information	

Date:	

E-mail to: jaia@mek.dtu.dk

CIA-CT comparison
Measurement report for Item 2

GENERAL INFORMATION

Participant short name	
Participant number	
Contact person	
Operator	

CT SCANNER

Instrument type (manufacturer)	
Maximum resolution in µm	
MPE values in µm (if known)	
Detector type (manufacturer)	
Detector type (line detector, area detector)	
Detector pixel size in µm	

SOFTWARE

Acquisition software	
Reconstruction software	
Analysis software	

SETUP AND SCANNING

Orientation of the item (+ photo)	
Hard filter: Pre-filter material and thickness in mm (if applied)	
ROI (Y/N)	
Temperature inside scanner before and after scannning in °C	
Number of scans per item	
Artefact for scale error correction (if applied) (+ photo)	
Voltage in kV	
Current in µA	
Power in W	
Focus spot size in µm (if known)	
Source-detector distance in mm	
Source-object distance in mm	
Geometrical magnification	
Original voxel size in µm	
No. of views (projections)	
Integration time in s	
No. of image averaging	
Binning	
Scanning time in min	

PROCESSING PARAMETERS

Reconstruction: As each reconstruction software enables to apply different setting parameters, you can provide the parameters which you find the most relevant for us to know. This can be for example in case you apply any beam hardening correction, noise reduction, etc.	
Scale error correction (Y/N)	
Voxel size after scale correction in µm	
Surface determination method (threshold)	
Data filtering (Y/N and what type of filter)	
Analysis done on volume data (original voxel data) or surface data (STL)	

UNCERTAINTY ASSESSMENT	**LIST OF UNCERTAINTY CONTRIBUTORS**
Method (indicate what of the following is used)	1)
1) GUM (analytical method)	2)
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3) ISO 15530-3 (substitution method)	...
4) VDI/VDE 2617-7 (simulation)	
5) Manufacturer specifications of the CT scanner	
6) Other	

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Processed CT data (e.g. .vgl)	
STL files (if relevant)	
Polar plots relative to *D1* and *R1*	
Photographs	
Other relevant information	

Date:	

E-mail to: jaia@mek.dtu.dk

CIA-CT comparison
Measurement report for Item 1

MEASUREMENT RESULTS All measurements must refer to 20ºC

Measurand	Average in mm	Expanded uncertainty in mm (k=2)
Diameter *D1 - unfiltered*		
Roundness *R1 - unfiltered*		
Diameter *D1 - 50 UPR*		
Roundness *R1 - 50 UPR*		
Diameter *D1 - 150 UPR*		
Roundness *R1 - 150 UPR*		
Length *L1*		

CIA-CT comparison
Measurement report for Item 2

MEASUREMENT RESULTS All measurements must refer to 20ºC

Measurand	Average in mm	Expanded uncertainty in mm (k=2)
Diameter *D1 - unfiltered*		
Roundness *R1 - unfiltered*		
Diameter *D1 - 50 UPR*		
Roundness *R1 - 50 UPR*		
Diameter *D1 - 150 UPR*		
Roundness *R1 - 150 UPR*		
Diameter D2 - unfiltered		
Roundness R2 - unfiltered		
Diameter D2 - 50 UPR		
Roundness R2 - 50 UPR		
Diameter D2 - 150 UPR		
Roundness R2 - 150 UPR		
Length *L1*		